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SUMMARY

A study has been made of the relative merits of aerodynamic braking, and combined rocket and aerodynamic braking of blunt nonlifting vehicles entering the earth's atmosphere at speeds varying from 25,000 to 60,000 feet per second. The study covered a wide range of heats of ablation of the heat shield, specific impulses of the rocket, entry angles, nose radii, and vehicle weight-to-area ratios. The assumed values of heat of ablation ranged from the heat required to vaporize Teflon to a value that is higher by a factor of 10. The values of specific impulse were appropriate for chemical, nuclear, and electrical propulsion devices. Radiation was the dominant mode of heat transfer for speeds in excess of about 40,000 feet per second. In treating this mode of heating, it was necessary to account for the self-absorption of shock-layer radiation and the shock-layer cooling that results from the radiation that is not absorbed.

For a Teflon heat shield and a chemical rocket, neither aerodynamic braking alone nor an optimum combination of rocket and aerodynamic braking provides an acceptable recovery of a blunt nonlifting vehicle returning to the earth's atmosphere at speeds in excess of 40,000 feet per second. Recovery of at least 50 percent of the initial weight for the higher speeds will require either an ablative heat shield with a heat of ablation that is a factor of 5 higher than the heat required to vaporize Teflon or a rocket with a performance that is 2.5 times higher than that expected for a nuclear device. When the heat of ablation is higher by a factor of 10, aerodynamic braking for a number of the entry and vehicle conditions matches the recovery performance offered by the combined braking of aerodynamic drag and an electrical propulsion device. In view of the results of a recent study (NASA TR R-185) which indicate that a conical body is more efficient than a blunt body for entry at the very high speeds, aerodynamic braking must be favored over combined braking for entry speeds up to 60,000 feet per second.

INTRODUCTION

Some space vehicles will be required to explore the planets in the solar system and then return to earth. Many of the problems associated with the entry of these vehicles into the earth's atmosphere have been examined and discussed in some detail by Allen (ref. 1). Entry speeds of these vehicles are predicted to be considerably in excess of earth escape speed. As the entry speed increases, radiation becomes the increasingly important mode of heat transfer and far exceeds convection. Recent studies have indicated that the dependence of radiative heat transfer on speed ranges from the eighth to the sixteenth power of speed, compared to approximately the third power for convective heat transfer. Thus the fraction of the total energy per vehicle unit mass that is converted to heat increases drastically with increasing speed. With the total energy per unit mass increasing as the square of the speed, the proportion of the vehicle mass required for heat protection leaves a vanishingly small proportion as payload. It is of interest to note that many natural objects enter the atmosphere at these high speeds. (See refs. 1-4.)

With this future to be faced by the designer of vehicles for high-speed entry of the earth's atmosphere, it is clear that some changes in the design of entry systems must be considered. One possible change that is examined herein is to employ rocket braking to slow the vehicle down before atmosphere entry rather than use aerodynamic braking alone. The relative merits of aerodynamic braking and combined rocket and aerodynamic braking are compared on the basis of the ratio of final to initial weight. The relative merits depend upon many factors, entry speed, entry angle, vehicle properties (both aerodynamic and physical), heat-shield effectiveness, and rocket performance. Accordingly, most of these factors were variables in the study. The vehicles considered were blunt nonlifting bodies.

NOTATION

A cross-sectional area of body, πR_b^2

C_D drag coefficient, $\frac{2\ \text{drag}}{\rho V^2 A}$

g gravitational acceleration

h altitude

I specific impulse

L initial effective length of body, $\frac{\text{body volume}}{A}$

R_b radius of body cross section

R_n nose radius of body

T thrust

t time

V speed

W body weight

w specific weight

γ flight-path angle relative to local horizontal

ρ atmospheric density

λ heat-transfer coefficient

ζ heat of ablation

Subscripts

c convective

E entry

F final (zero altitude)

I initial

o sea level

n nonequilibrium

r radiative

ANALYSIS

Relations for Aerodynamic Braking

Equations of motion and mass loss.- Analyses of the motion, heating, and ablation of bodies in flight through the atmosphere have been presented in a number of reports (e.g., refs. 1-7). The equations of motion and mass loss for a body in a relatively steep, straight-line trajectory can be expressed as

$$\frac{W}{g_o}\frac{dV}{dt} = -\frac{C_D}{2}\rho V^2 A \tag{1a}$$

$$\frac{\zeta}{g_o}\frac{dW}{dt} = -\frac{\lambda}{2}\rho V^3 A \tag{1b}$$

where

λ heating rate per unit area/$(1/2)\rho V^3$

ζ heating rate/ablation rate

With the introduction of the expression for a straight-line trajectory

$$dt = -\frac{dh}{V \sin \gamma_E} \tag{2}$$

equations (1a) and (1b) become

$$\frac{dV}{dh} = \frac{\rho g_o A C_D V}{2W \sin \gamma_E} \tag{3a}$$

$$\frac{dW}{dh} = \frac{\rho g_o A \lambda V^2}{2\zeta \sin \gamma_E} \tag{3b}$$

The foregoing two simultaneous, nonlinear, first-order differential equations are solved numerically by use of an electronic digital computer to obtain the ratio of final to initial weight W_F/W_E. In obtaining the numerical solutions, it was found desirable to use the following equations which were obtained from equations (3a) and (3b) by introducing the entry parameter $(W_E/C_D A R_n)\sin \gamma_E$:

$$\left(\frac{W}{W_E}\right)\frac{dV}{dh} = \frac{\rho g_o V}{2R_n(W_E/C_D A R_n)\sin \gamma_E} \tag{4a}$$

$$\frac{d(W/W_E)}{dh} = \frac{\rho g_o \lambda V^2}{2\zeta C_D R_n(W_E/C_D A R_n)\sin \gamma_E} \tag{4b}$$

The desirability of introducing the parameter $(W_E/C_D A R_n)\sin \gamma_E$ is that, for a range of values of R_n, one set of values of the parameter will suffice to cover realistic ranges of vehicle densities, lengths, and entry angles.

Evaluation of C_D and λ.- In evaluating the coefficients C_D and λ in the foregoing equations it is necessary to specify the geometry of the body nose. The nose shape (fig. 1) assumed in this analysis is a spherical segment for which $R_n/R_b = 2$. It is further assumed that the nose shape does not change as the body ablates. The drag coefficient of a nonlifting body of the assumed nose shape, as given by Newtonian theory, is $C_D = 1.75$.

The heat-transfer coefficient is composed of the following contributions which are evaluated as described below:

$$\lambda = \lambda_r + \lambda_n + \lambda_c \tag{5}$$

(1) λ_r, equilibrium gas-cap radiation: The results of references 8 and 9 are used to calculate the equilibrium radiative heat-transfer coefficient. It is assumed that λ_r was constant over the nose (i.e., the stagnation-point value was assumed for all points). This assumption probably provides a sizable degree of conservatism in the calculations; the values of λ_r are overestimated by perhaps as much as a factor of 2 on the basis of the radiative heat-transfer distributions presented in reference 10.

It is to be noted, however, that the results presented in reference 10 are not directly applicable to all entry and vehicle conditions considered in the present analysis. The results of reference 10 apply only to conditions for which self-absorption of shock-layer radiation and shock-layer cooling by radiation are not significant.

(2) λ_n, nonequilibrium gas-cap radiation: The out-of-equilibrium effects are obtained by extrapolation of existing experimental data (e.g., refs. 11 and 12).

(3) λ_c, convection of heat across the boundary layer: The boundary layer is assumed to be laminar. An averaged convective heat-transfer coefficient is used for the complete nose. A reduction in convective heating resulting from ablation is not taken into account since convective heating itself is a small proportion of the total heat transfer to the body for entry speeds in excess of escape speed. For the same reason, account is not taken of the effect on the convective heating of the cooling of the shock layer by radiation. In view of these circumstances, the convective heating coefficient averaged over the nose is approximated by the following simple relation (ref. 6):

$$\lambda_c = \frac{0.000391}{\sqrt{(\rho/\rho_o)R_n}} \qquad R_n \text{ in ft} \tag{6}$$

With the individual components evaluated as indicated above, the value of λ sometimes exceeds unity, a clearly untenable result since the heat transfer to the body will then exceed the flux of energy into the shock layer. In order to avoid this occurrence, adjusted values of λ are obtained by use of the following equation:

$$\lambda = \lambda' e^{-2\lambda'} + \left(1 - e^{-\lambda'}\right)^2 \tag{7}$$

where λ' is the unadjusted value.

Values of λ were calculated as described above; the results are presented in figure 2.

Relations for Rocket Braking

The equation for rectilinear motion of a rocket in gravity-free space is

$$\frac{W}{g_o}\frac{dV}{dt} = -T \tag{8}$$

The rocket thrust is given by

$$I\frac{dW}{dt} = -T \tag{9}$$

When the above equations are combined,

$$\frac{dW}{W} = \frac{dV}{Ig_o} \tag{10}$$

For constant specific impulse (Ig_o = constant) it follows that

$$\frac{W_E}{W_I} = e^{-(V_I - V_E)/Ig_o} \tag{11}$$

where V_I is the initial speed of the vehicle, and V_E is the speed at the time the propellant burns out, and W_I and W_E are the weights corresponding to V_I and V_E.

Combined Aerodynamic and Rocket Braking

The two types of braking are combined in the following manner. Rocket braking is used initially to decelerate the vehicle from the initial speed V_I to V_E, at which rocket burnout occurs and the vehicle enters the atmosphere. It is desired to maximize the ratio of recoverable weight to entry weight W_F/W_E for a given set of entry conditions. Maximum values of the ratio are determined with the use of the following expression:

$$\frac{W_F}{W_I} = \left(\frac{W_E}{W_I}\right)\left(\frac{W_F}{W_E}\right) \tag{12}$$

The first ratio on the right side of the equation is the weight ratio for rocket braking and the second is the ratio for aerodynamic braking. For a given set of entry conditions, values of W_F/W_I are calculated for various assumed values of V_E, and are plotted as a function of V_E to determine the maximum value of W_F/W_I. The number of calculations for a range of entry speeds is greatly reduced by the fact that the optimum value of V_E is independent of the initial speed V_I. This can be shown by differentiating equation (12) with respect to V_E, setting the derivative equal to zero, and using equation (11). One obtains

$$\frac{d(W_E/W_I)}{dV_E} = \left[\frac{d(W_F/W_E)}{dV_E} + \left(\frac{W_F}{W_E}\right)\frac{1}{Ig_o}\right]e^{-(V_I - V_E)/Ig_o} = 0$$

or

$$\frac{d(W_F/W_E)}{dV_E} + \left(\frac{W_F}{W_E}\right)\frac{1}{Ig_o} = 0 \tag{13}$$

The conditions for optimum recoverable mass ratio imposed by this equation are clearly independent of V_I.

APPLICATION OF ANALYSIS

Numerical calculations were made for initial speeds ranging from 25,000 to 60,000 feet per second for the following combinations of parameters:

Nose radius, R_n: 1.5, 3.0, 7.0, and 15 feet

[1]Heat of ablation, ζ: 2×10^7, 10×10^7, and 20×10^7 ft^2/sec^2

Entry parameter, $(W_E/C_DAR_n)\sin\gamma_E$: 3.2, 9.2, 18.4, and 36.8 lb/ft^3

Specific impulse, I: 400, 800, and 4,000 sec

It was assumed for these calculations that the effective ablation of each body began at 260,000 feet and ended at zero altitude.

RESULTS AND DISCUSSION

The results, in the form of the ratio of recoverable weight to initial weight as a function of initial speed, for aerodynamic braking alone and for optimum combinations of rocket and aerodynamic braking are presented in figures 3, 4, and 5. The results for aerodynamic braking alone are identified by $I = 0$; the initial speed is the atmosphere entry speed. The optimum rocket cutoff speed (the atmosphere entry speed for combined braking) for each combination of rocket and aerodynamic braking is identified by the point at which the curve for that combination merges with the curve for $I = 0$. For initial speeds greater than the optimum rocket cutoff speed, rocket braking should be used to slow the body prior to entering the atmosphere. For lower initial speeds it is more efficient to use aerodynamic braking alone.

To serve as a reference in the subsequent consideration of the results, it is desirable to relate the assumed heats of ablation and rocket specific impulses to particular ablative materials and types of rockets, respectively. The low heat of ablation (2×10^7 ft^2/sec^2) is approximately equal to the heat required to vaporize Teflon; whereas, the high value (20×10^7 ft^2/sec^2) is about 25 percent higher than the heat of vaporization of quartz at 3,000° K, and within the low end of the range of values quoted for the heat of sublimation of graphite (which range from about 12 to 50×10^7 ft^2/sec^2, depending upon the molecular weight of the carbon vapors). The low rocket specific impulse (400 sec) is representative of high-performance chemically fueled rockets, the intermediate (800 sec) of nuclear rockets, and the high (4,000 sec) of electrical propulsion devices.

As shown in figure 3, aerodynamic braking is clearly inferior to combined braking when a Teflon heat shield is used. The combination of aerodynamic braking and rocket braking with a chemically fueled rocket provides higher weight ratios at speeds in excess of 34,000 to 45,000 feet per second,

[1]The conversion to Btu/lb is as follows: $(\zeta, \text{Btu/lb}) = 4\times10^{-5}\ (\zeta, \text{ft}^2/\text{sec}^2)$

depending upon the vehicle and entry conditions. The resulting ratios, however, are not very impressive; for example, for a speed of 60,000 feet per second, the recoverable weight is about 20 percent of the initial weight, or less, for an optimum combination of rocket and aerodynamic braking. It can be seen that one must look forward to the development of electrical propulsion devices (I = 4,000 sec) before a more acceptable recovery performance is attained. For a nuclear device (I = 800 sec), the recoverable weight for an entry speed of 60,000 feet per second ranges from 18 to 35 percent of the initial weight, whereas an electrical device offers recoverable weights of 50 to 75 percent of initial weight. In the latter case, the rocket cutoff speeds are generally close to satellite speed, which suggests the interesting possibility of leaving the propulsion device in orbit for subsequent reuse.

The results for the intermediate value of heat of ablation (fig. 4) show that combined braking is generally superior to aerodynamic braking alone, only when the highest performance rocket (I = 4,000 sec) is used. An interpolation of the results indicates that, for equal recovery performance, the rocket specific impulse would have to be about 2,000 seconds. This value is about 2.5 times that expected for nuclear devices. In contrast, the intermediate value of heat of ablation (10×10^7 ft^2/sec^2) is only 60 percent of the heat of vaporization of an existing ablative material, quartz.

For the case of the high heat of ablation (fig. 5), the recovery performance provided by aerodynamic braking alone is, for some conditions, the equal of that provided by combined braking with high rocket specific impulse. The high heat of ablation appears to be within the capability of current technology for ablative heat shields, being only 25 percent higher than the heat of vaporization of quartz and in the lower end of the range of values quoted for the heat of sublimation of graphite. The high rocket specific impulse, on the other hand, is well beyond current rocket technology.

The relative merits of aerodynamic braking, and combined aerodynamic and rocket braking for an initial speed of 60,000 feet per second are summarized in the following table:

Specific impulse, sec	Cutoff speed, ft/sec	Weight ratio, W_F/W_I
$\zeta = 2 \times 10^7$ ft^2/sec^2		
0	---	0 - 0.08
400	34,000 - 45,000	0.06 - 0.18
800	30,000 - 40,000	0.18 - 0.35
4000	25,000 - 31,000	0.49 - 0.75
$\zeta = 10 \times 10^7$ ft^2/sec^2		
0	---	0.24 - 0.69
4000	30,000 - 39,000	0.71 - 0.80
$\zeta = 20 \times 10^7$ ft^2/sec^2		
0	---	0.52 - 0.83
4000	33,000 - 60,000	0.75 - 0.83

In addition to these effects, on recoverable weight ratio, of heat of ablation and rocket specific impulse, there are also some interesting effects of nose radius. Rather than use constant values of the entry parameter as a basis of comparison (as in figs. 3, 4, and 5), it will be more meaningful to use constant recoverable weight. Comparison of the effect of nose radius at a constant value of the entry parameter is misleading in that vehicles of differing total weight are compared (assuming that entry angle remains constant).

Figure 6 illustrates, for aerodynamic braking only, the effect of nose radius on the ratio of recoverable to initial weight for constant recoverable weight and entry angle (i.e., $W_F \sin \gamma_E$ is constant). The effect of increasing nose radius is noted to be unfavorable. This result is generally typical for other combinations of V_E, ζ, and $w \sin \gamma_E$.

Also shown in figure 6 are two upper boundaries to the values of weight ratio. One boundary is based on a limitation of impact speed for which an arbitrary limit of 1,000 feet per second was assumed. The other boundary is based on a limitation on body length imposed by a requirement for static aerodynamic stability. This requirement is met by having the center of gravity ahead of the center of curvature of the nose (assuming that only the pressures on the nose are significant). This condition is met, for the nose shape assumed in this study, by using values of L/R_b less than 4; in order to be conservative, a value of 3 was used in defining the boundary. It will be noted that these two boundaries together define the optimum nose radius for a given recoverable weight. (Note also that $L/R_b < 3$ on the impact velocity boundary.) Both the optimum nose radius and the limit weight ratio increase with increasing recoverable weight where the static-stability requirement ($L/R_b = 3$ boundary) is limiting; whereas, neither quantity varies appreciably where the impact-velocity boundary serves as a limit.

Limit values of recoverable weight ratio for combined aerodynamic and rocket braking are compared in figure 7 with the corresponding values for aerodynamic braking alone. The values for combined braking are the maximum attainable with each particular combination of heat of ablation and rocket specific impulse. (For some conditions, the dotted contours of constant $W_F \sin \gamma_E$ are not shown near $I = 0$; the reasons for these omissions are that the contours do not vary monotonically near $I = 0$, and their actual variations are not too significant.) These results show, as one would expect, that the effect of nose radius on limit mass ratio generally diminishes with either increasing heat of ablation or specific impulse. Note also that there is a corresponding reduction in the variation of weight ratio with the recoverable weight. Consequently, the effect of nose radius (or recoverable weight) on the relative merits of aerodynamic braking, and combined aerodynamic and rocket braking is lessened as both the heat of ablation and specific impulse are increased to the highest values considered in the study. Considering the relative merits of the two types of braking, rather than the effects of nose radius thereon, the limit weight ratios provide qualitatively the same conclusions as those gained from the weight ratios presented in figures 3, 4, and 5.

CONCLUDING REMARKS

From the results of the study presented herein it is concluded that if Teflon is used as an ablative heat shield, aerodynamic braking alone or in optimum combination with a chemically fueled rocket is unacceptable for a blunt, nonlifting vehicle returning to the earth's atmosphere at speeds in excess of about 40,000 feet per second. For aerodynamic braking alone the ratio of recoverable to initial weight rapidly diminished toward zero as the entry speed was increased toward 60,000 feet per second. For optimum combinations of aerodynamic braking and rocket braking, the weight ratios for an initial speed of 60,000 feet per second were unacceptably low (6 to 18 percent).

The achievement of recoverable weight ratios of at least 50 percent for initial speeds in the range of 40,000 to 60,000 feet per second will require either an ablative heat shield or a rocket with a performance fivefold higher than that of Teflon, or a chemically fueled rocket, respectively. A fivefold higher heat of ablation than that of Teflon appears to be well within the capability of several known ablative materials (e.g., quartz and graphite). An increase in rocket specific impulse by a factor of 5 over that for a chemically fueled rocket is a factor of 2.5 higher than that expected for a nuclear rocket, or one-half of that expected for electrical propulsion.

Extensive effort is already being made to develop higher performance rockets, but only limited attention and effort has been directed toward the problem of developing ablative heat shields for high radiative heating environments. A property of importance in addition to heat of ablation is resistance to the thermal shock imposed by the high heating-rate environment. A cursory consideration of the limited information on the properties of graphite indicates that it may prove to be a very promising material for the high radiative heating environment. The attractive features of graphite are its apparently high heat of sublimation. Widely varying values of heat of sublimation are quoted in the literature; the range is from 6 to 25 times the heat required to vaporize Teflon. The high thermal conductivity of graphite, a property which has made it unfavorable for use on entry vehicles designed to enter the earth's atmosphere at escape speed or less, may prove to be very desirable from the standpoint of minimizing the temperature gradient at the surface, and, hence, the thermal stresses. With graphite forming the ablative layer for the very high speed portion of a trajectory, an underlayer of a composite charring material might provide the protection for the remainder of the trajectory.

Alternative possibilities for developing ablative heat shields for high radiative heating are (1) an ablative heat shield which reflects the radiation, while blocking convective heating as the result of vaporization, and (2) a metallic heat sink over a layer of ablative material, the metallic layer to reflect the radiation and absorb the convective heat during the high radiative heating period, and the underlying ablative layer to afford the protection for the remainder of the trajectory. Two examples of the first approach are property oriented, reflecting particles distributed through a transparent ablative material, and multilayers of transparent ablative material with a very thin reflective film between each layer. Achievement of the desired high reflectivity appears uncertain, however, because most of the radiation will be in the ultraviolet region of the spectrum where few materials are known to have high reflectivity. The second approach might prove to be inefficient because of the weight of the material required to absorb the convective heating during the high radiative heating period. Since rejection of the radiative heating load might be achieved by these two approaches, they are worthy of serious attention.

A completely different approach to the problem of entry at very high speeds that has been suggested (ref. 13) is the use of a conical nose to reduce the radiative heating. A penalty in convective heating will be incurred, but generally an ablative heat shield will be sufficiently more effective for convective than for radiative heating so that a net gain is realized. In view of this finding and the results of the present study for blunt bodies, aerodynamic braking must be favored over combined aerodynamic and rocket braking for speeds up to at least 60,000 feet per second.

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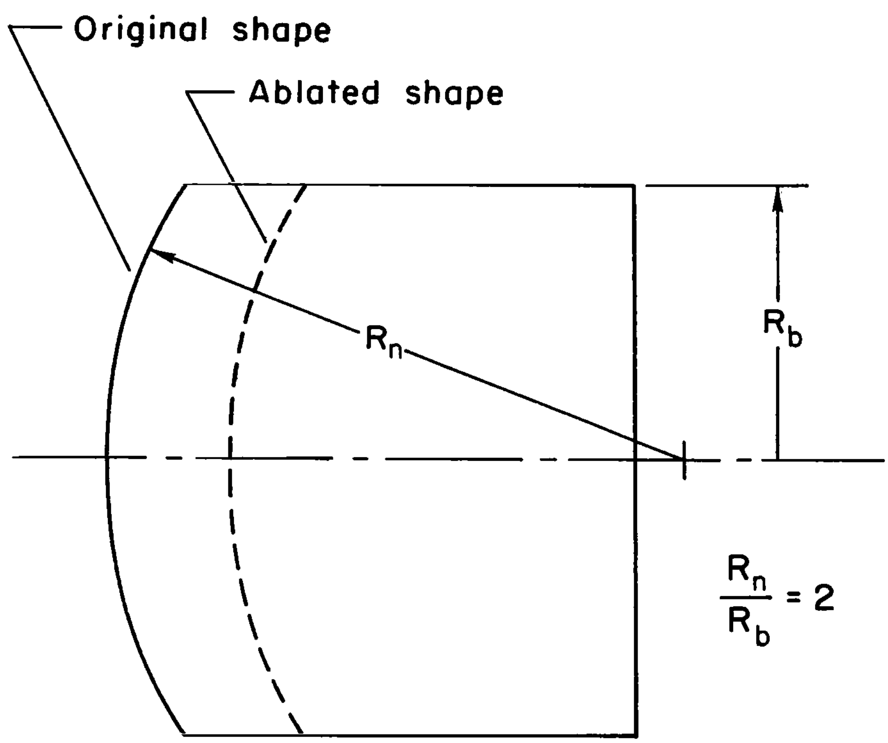
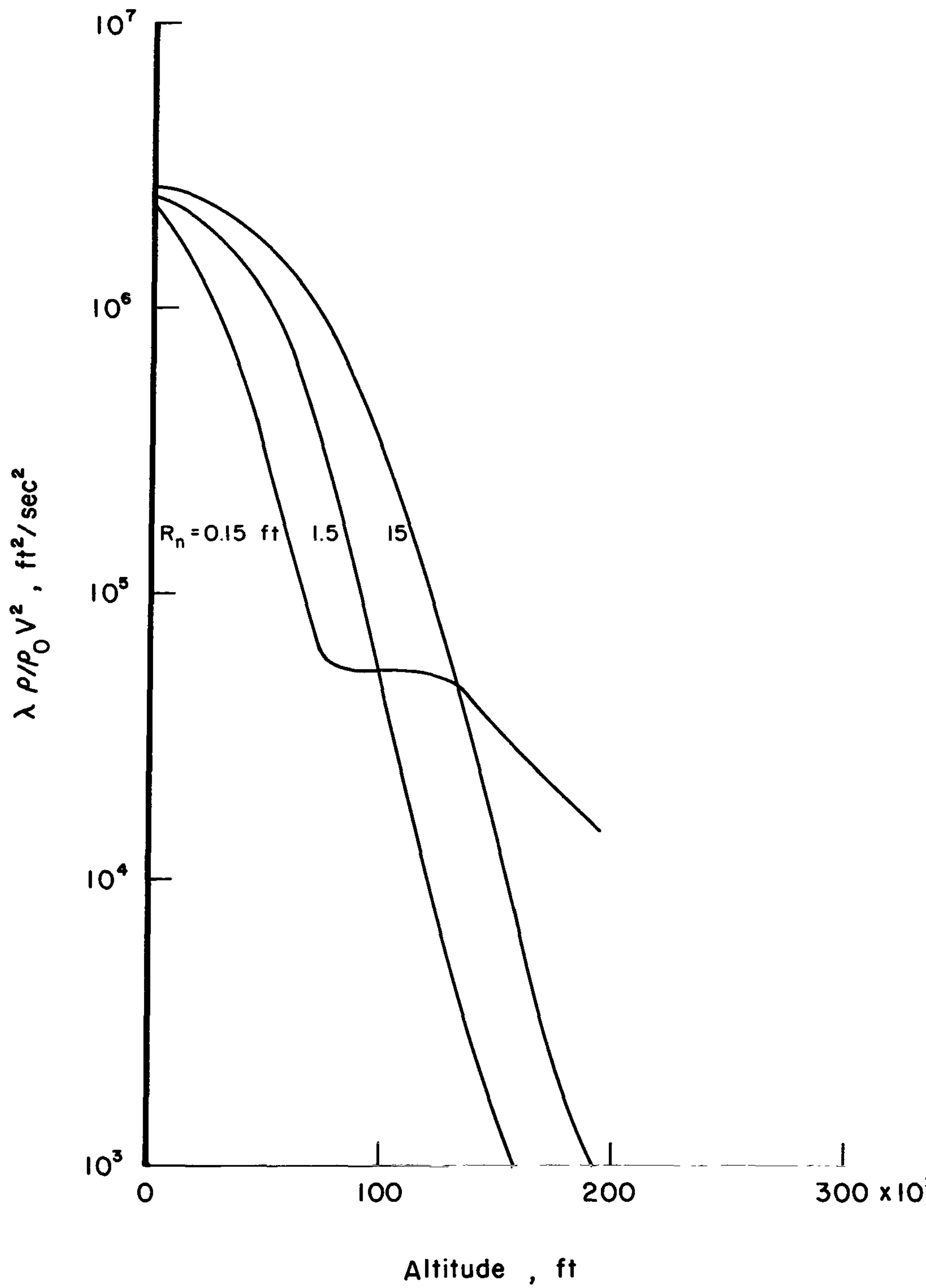
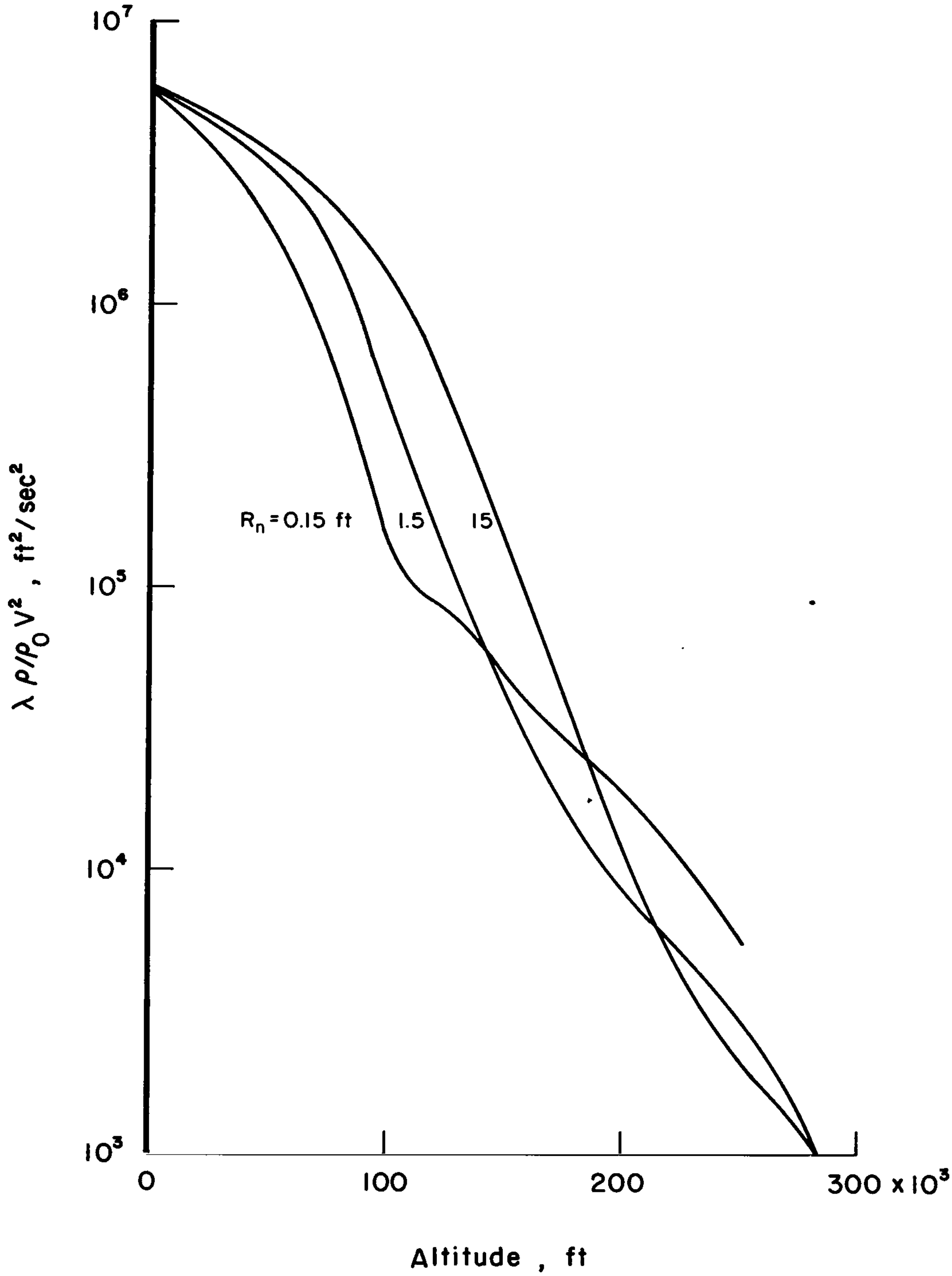


Figure 1.- Body geometry.



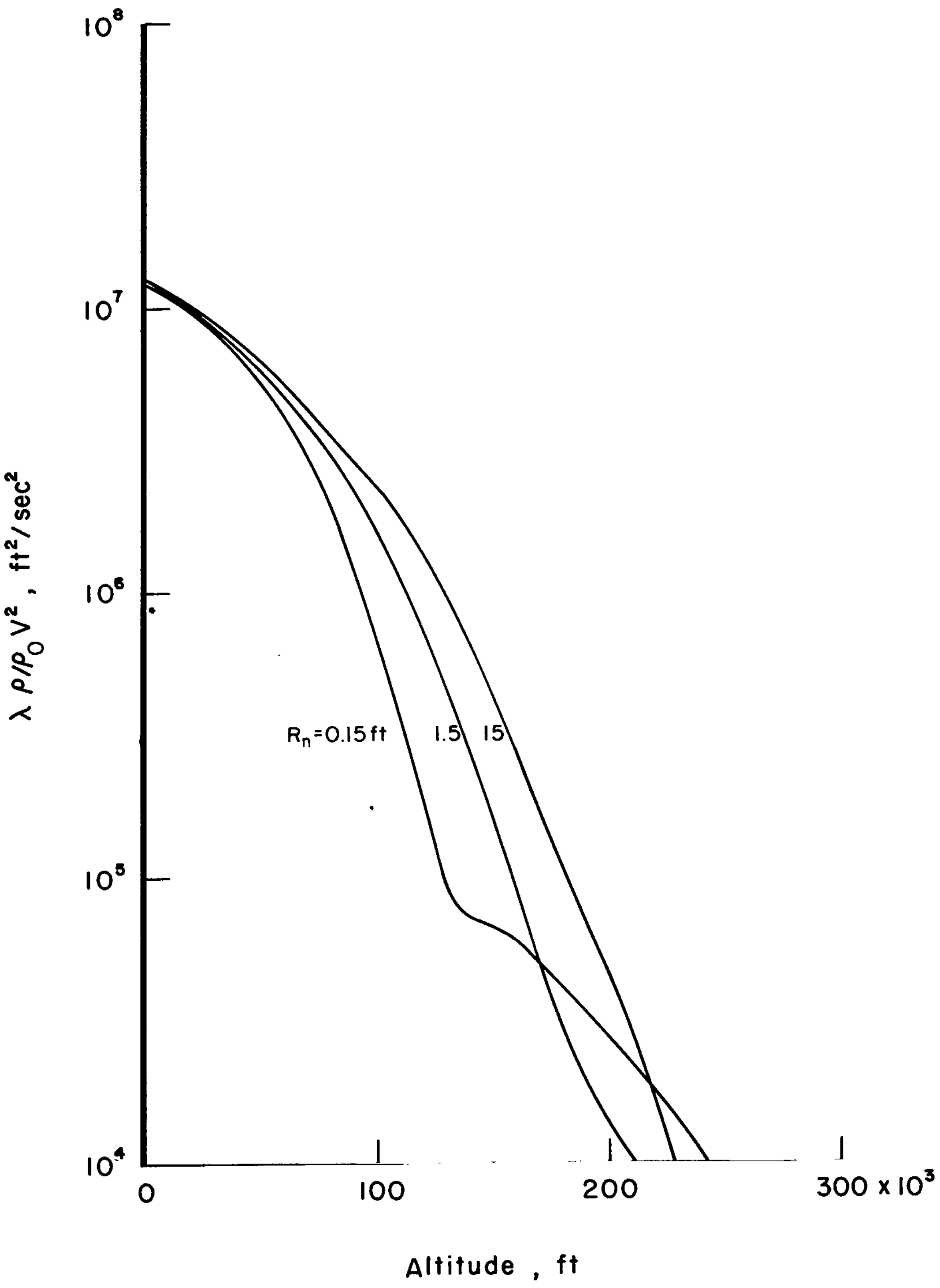
(a) V_E = 30,000 ft/sec

Figure 2.- Values of the heat-transfer parameter $\lambda\rho/\rho_o V^2$ for various speeds, altitudes, and nose radii.



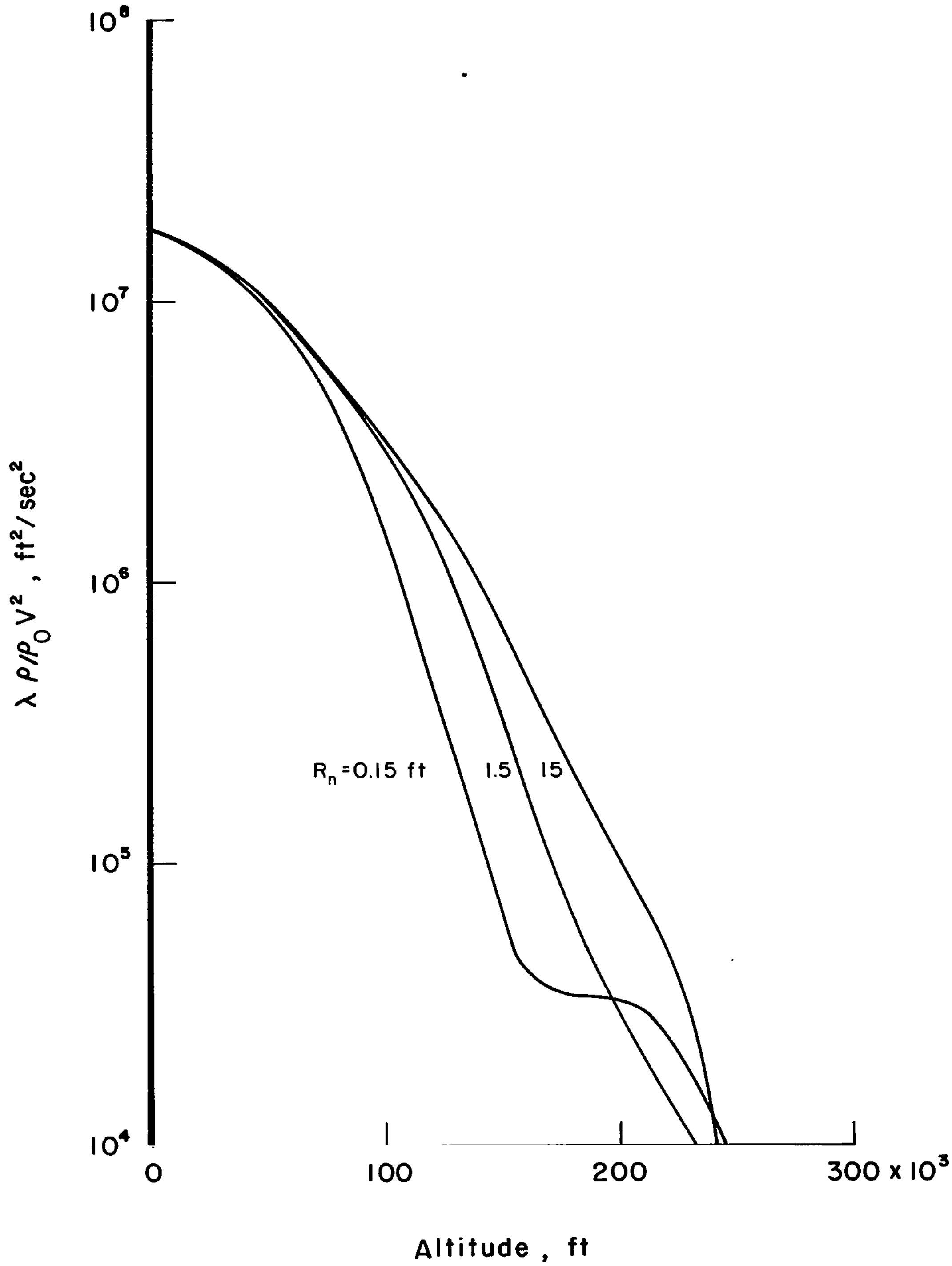
(b) V_E = 35,000 ft/sec

Figure 2.- Continued.



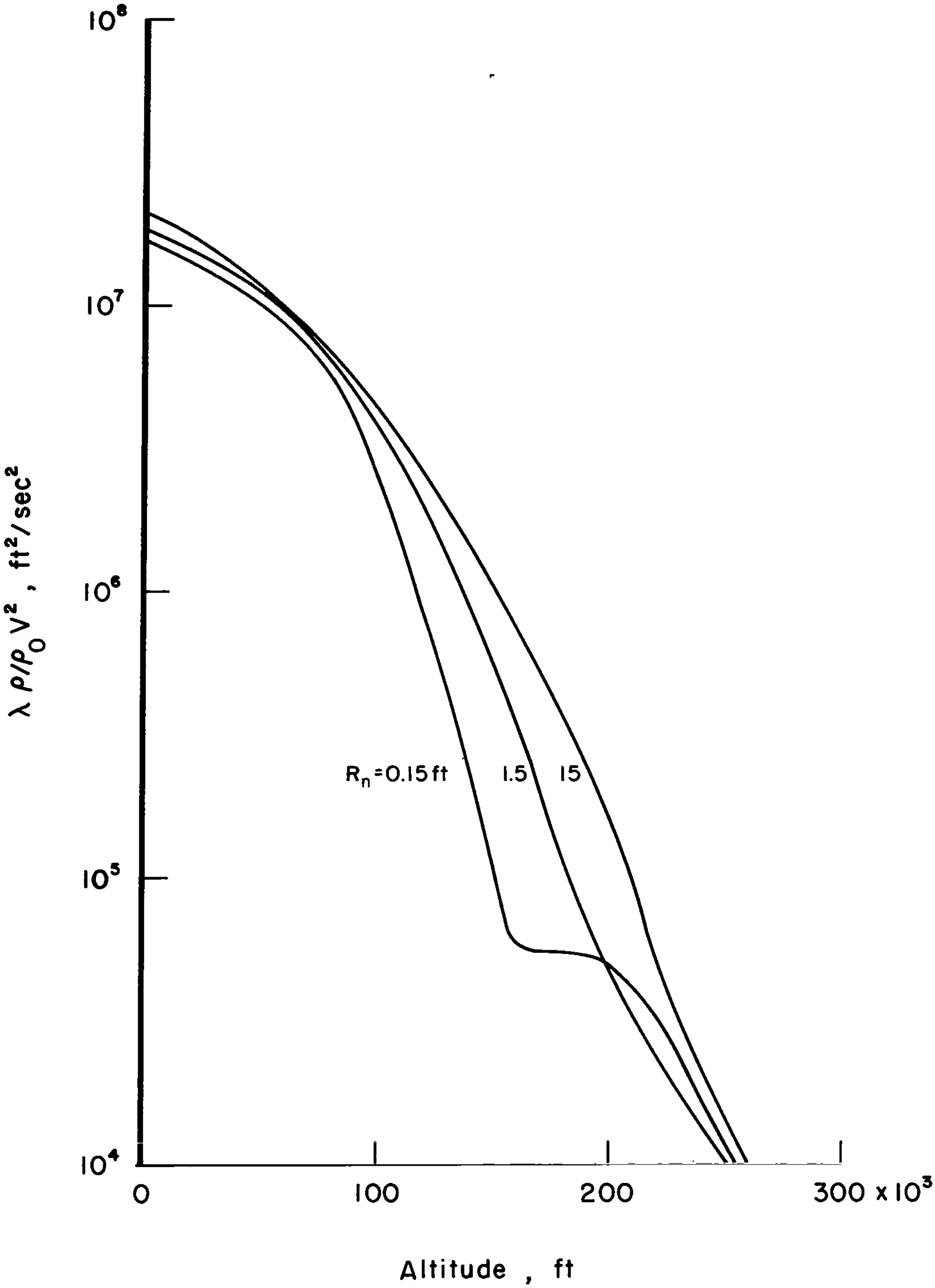
(c) V_E = 40,000 ft/sec

Figure 2.- Continued.



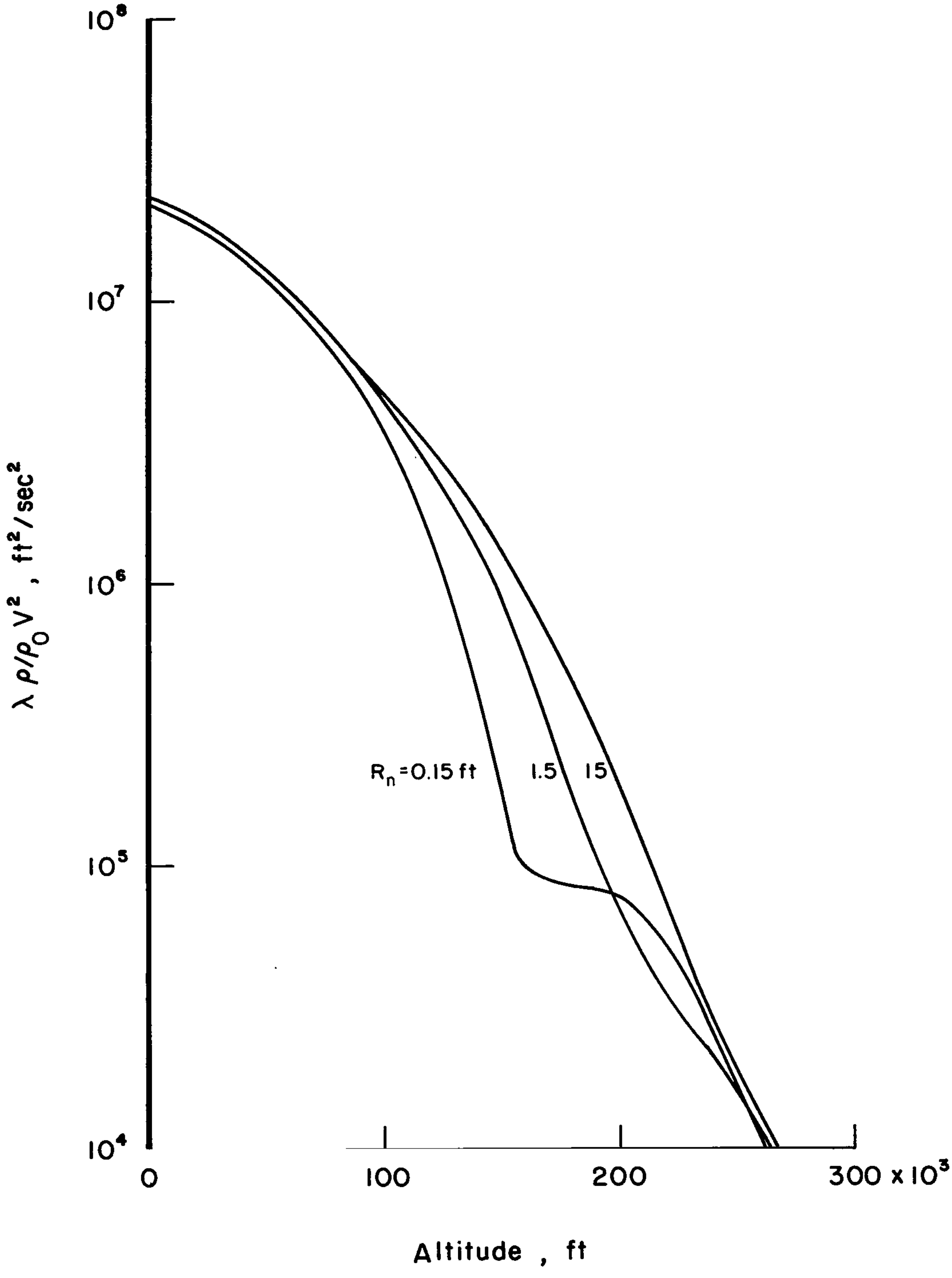
(d) V_E = 45,000 ft/sec

Figure 2.- Continued.



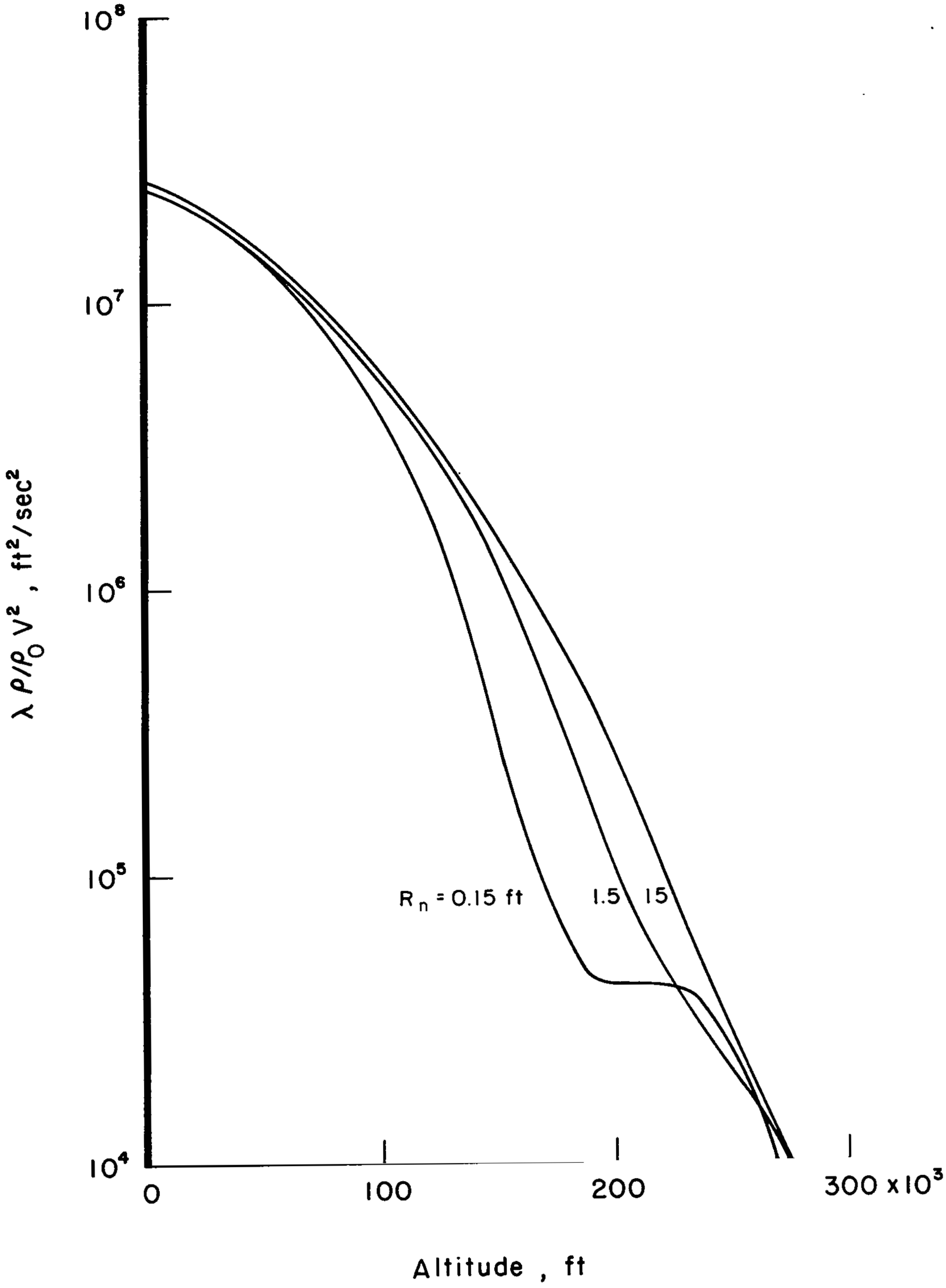
(e) V_E = 50,000 ft/sec

Figure 2.- Continued.



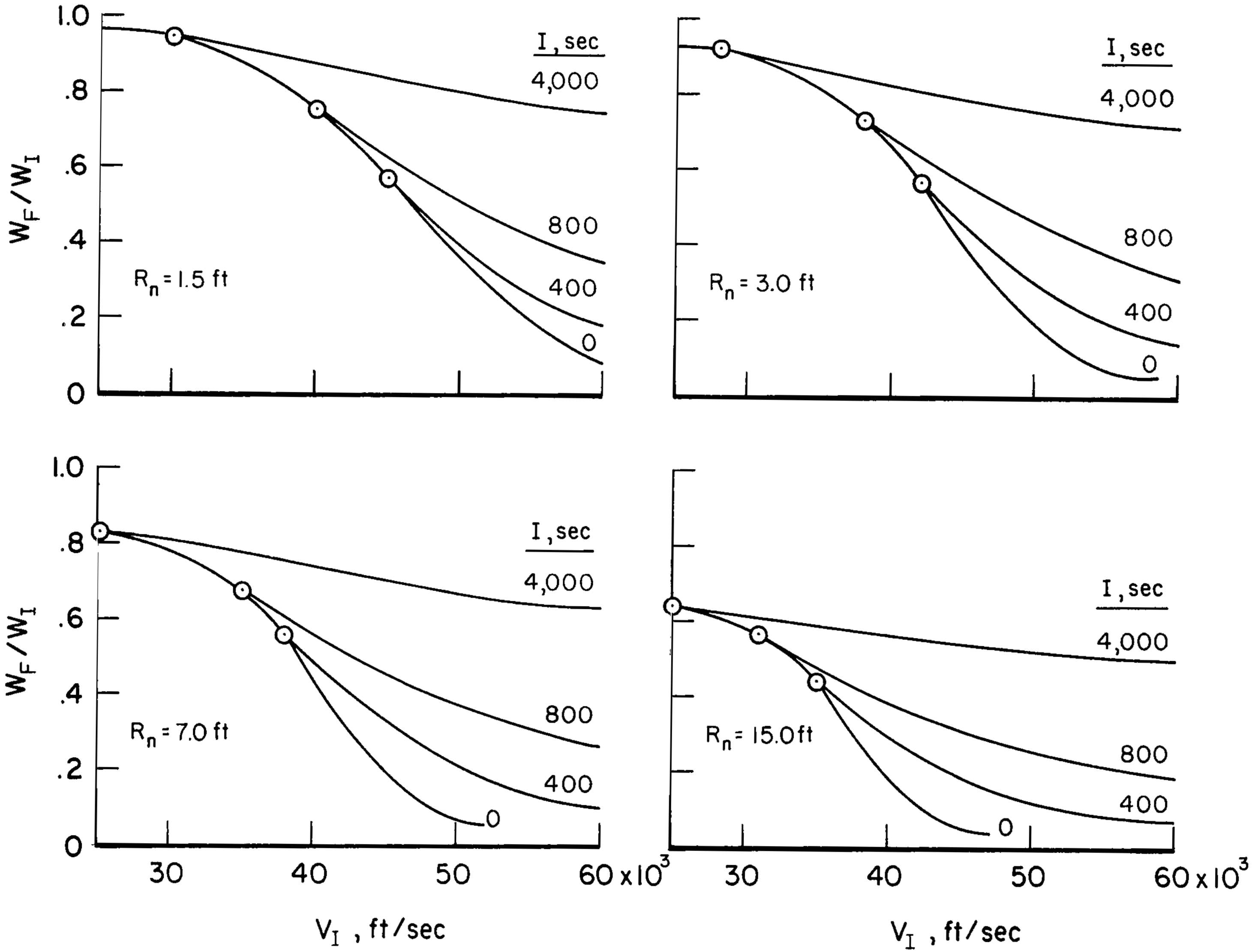
(f) V_E = 55,000 ft/sec

Figure 2.- Continued.



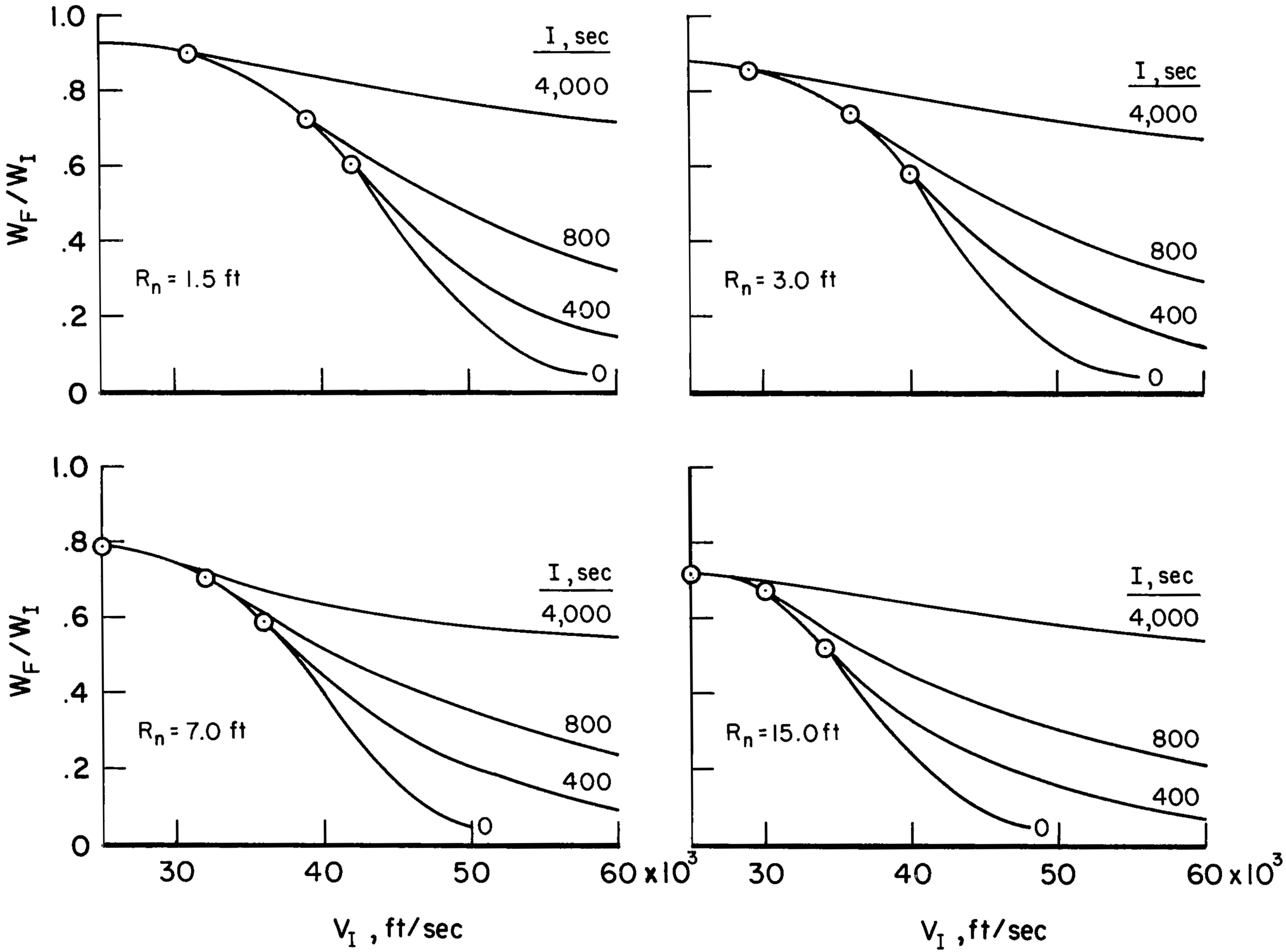
(g) V_E = 60,000 ft/sec

Figure 2.- Concluded.



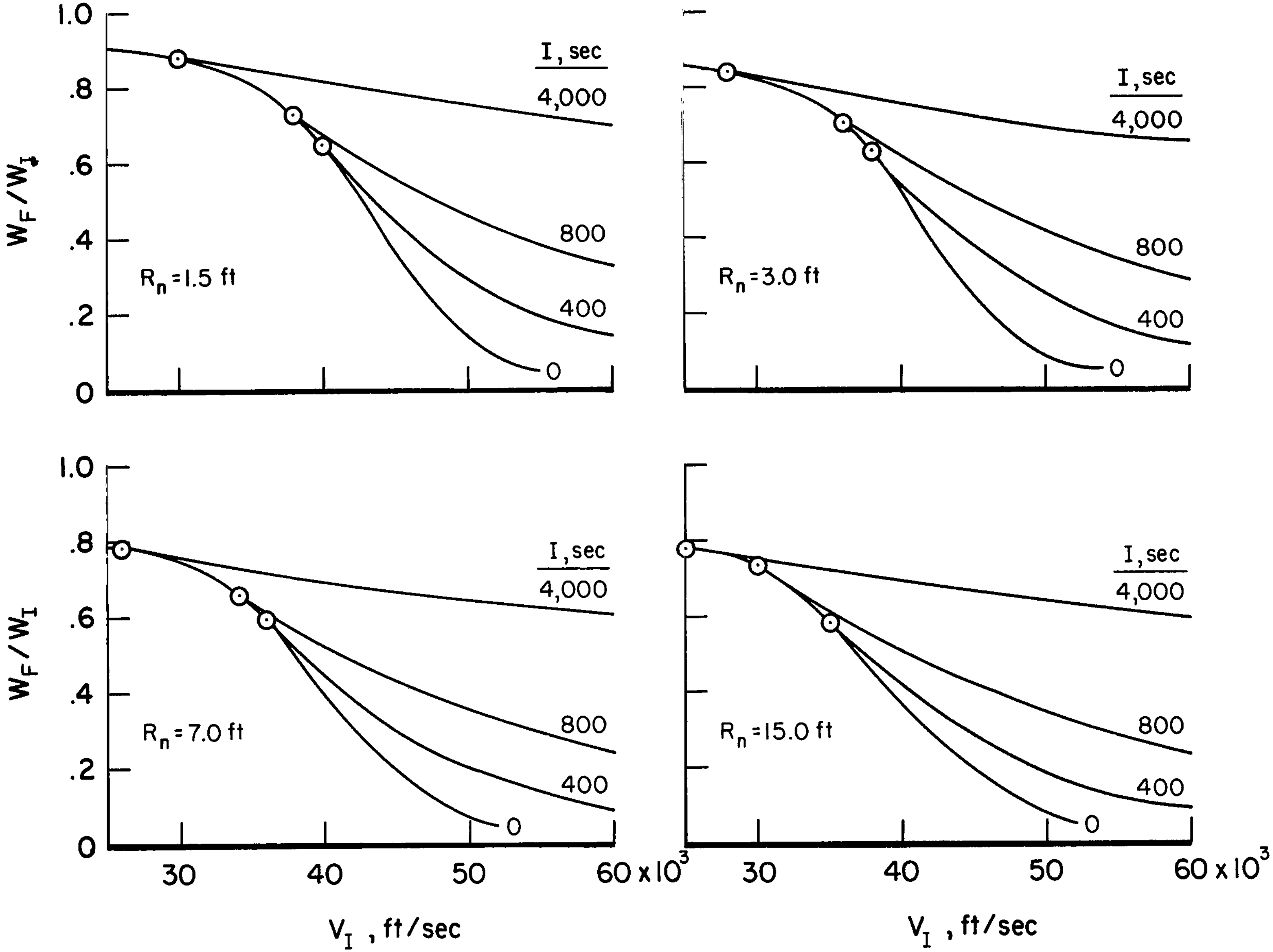
(a) $\frac{W_E}{C_D A R_n} \sin \gamma_E = 3.2 \text{ lb/ft}^3$

Figure 3.- Weight ratios for aerodynamic braking alone, and for optimum combinations of aerodynamic and rocket braking; $\zeta = 2\times10^7$ ft^2/sec^2.



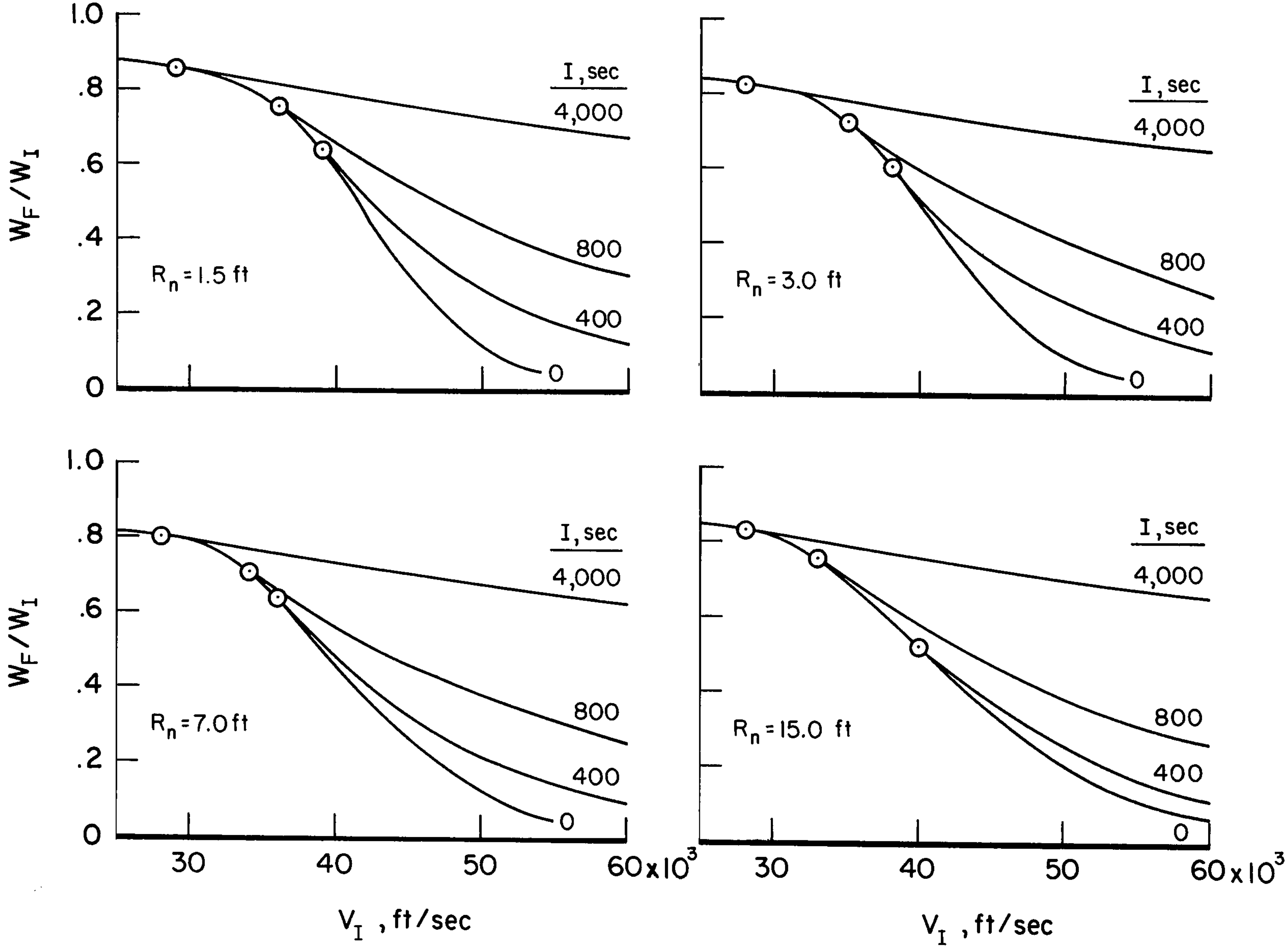
(b) $\frac{W_E}{C_D A R_n} \sin \gamma_E = 9.2 \text{ lb/ft}^3$

Figure 3.- Continued.



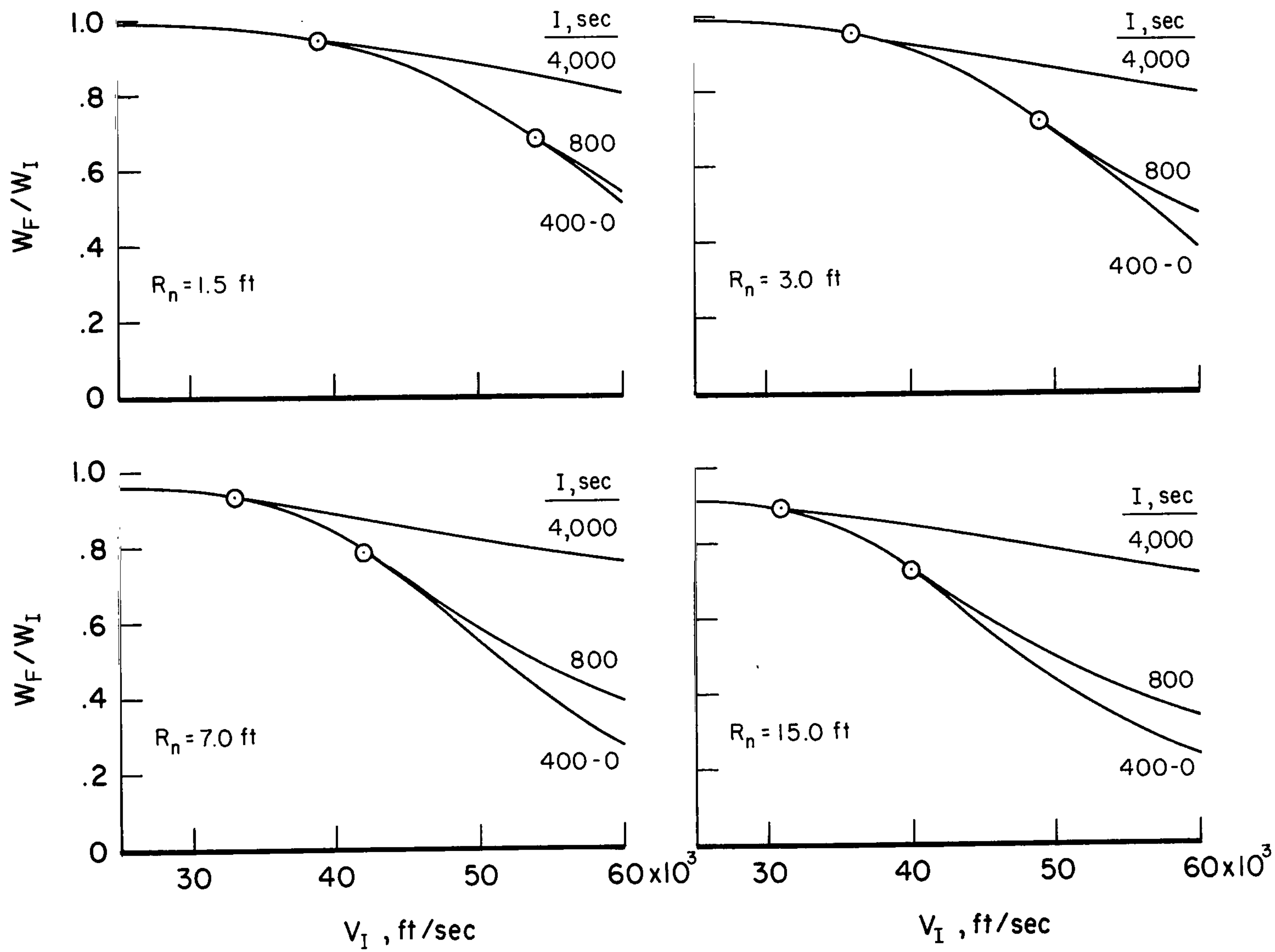
(c) $\frac{W_E}{C_D A R_n} \sin \gamma_E = 18.4 \text{ lb/ft}^3$

Figure 3.- Continued.



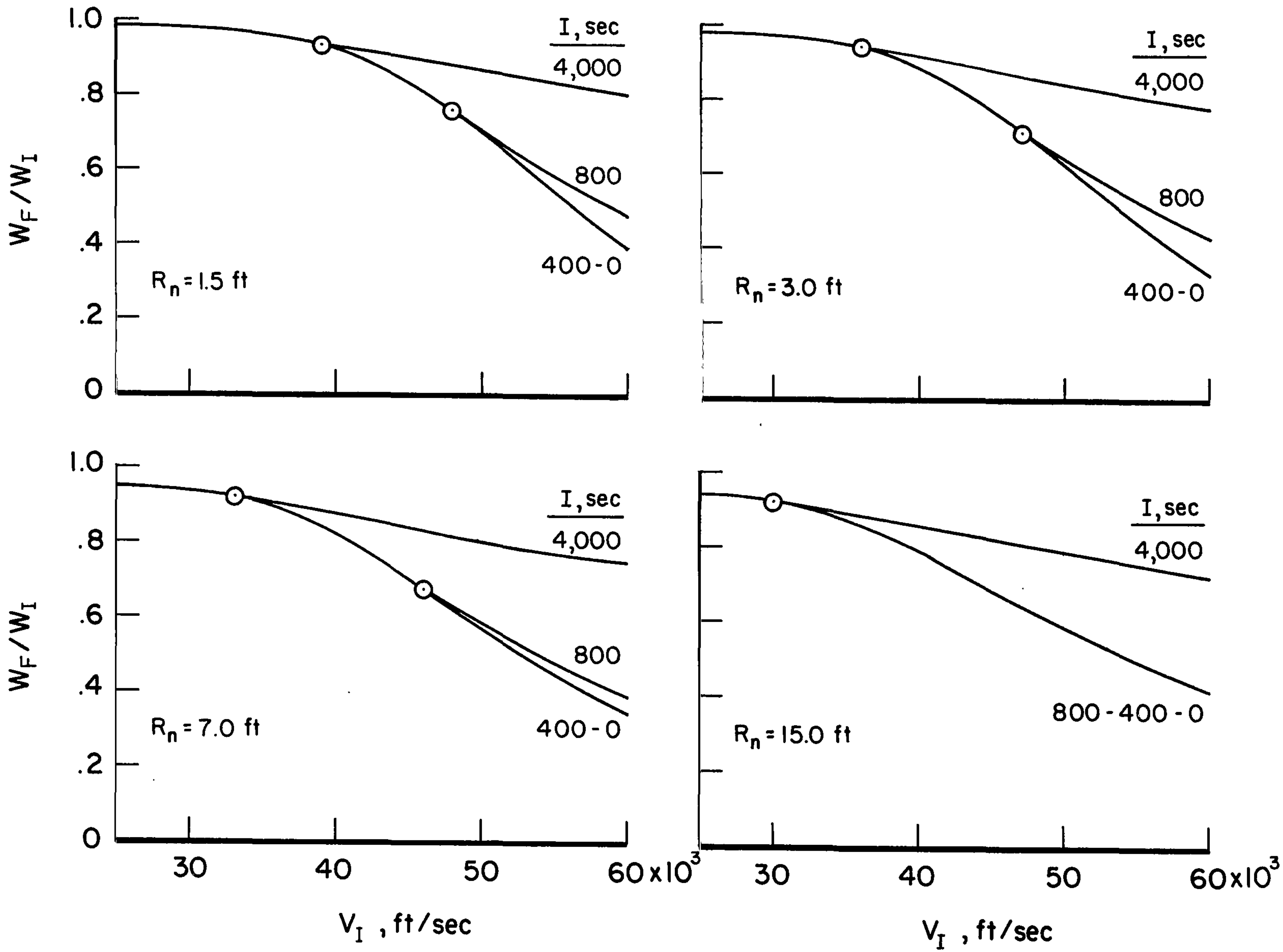
(d) $\frac{W_E}{C_D A R_n} \sin \gamma_E = 36.8 \text{ lb/ft}^3$

Figure 3.- Concluded.



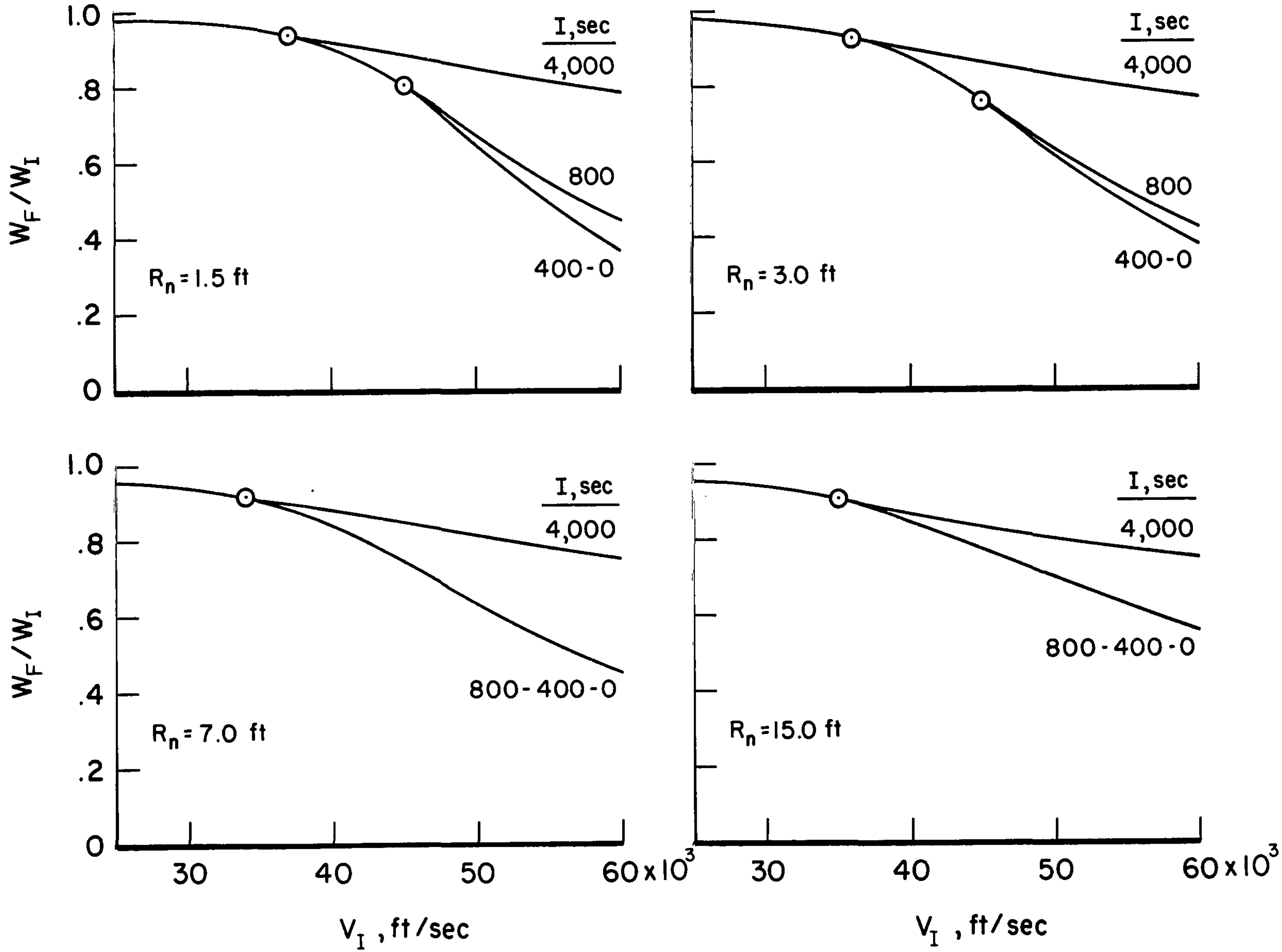
(a) $\frac{W_E}{C_D A R_n} \sin \gamma_E = 3.2 \text{ lb/ft}^3$

Figure 4.- Weight ratios for aerodynamic braking alone, and for optimum combinations of aerodynamic and rocket braking; $\zeta = 10 \times 10^7 \text{ ft}^2/\text{sec}^2$.



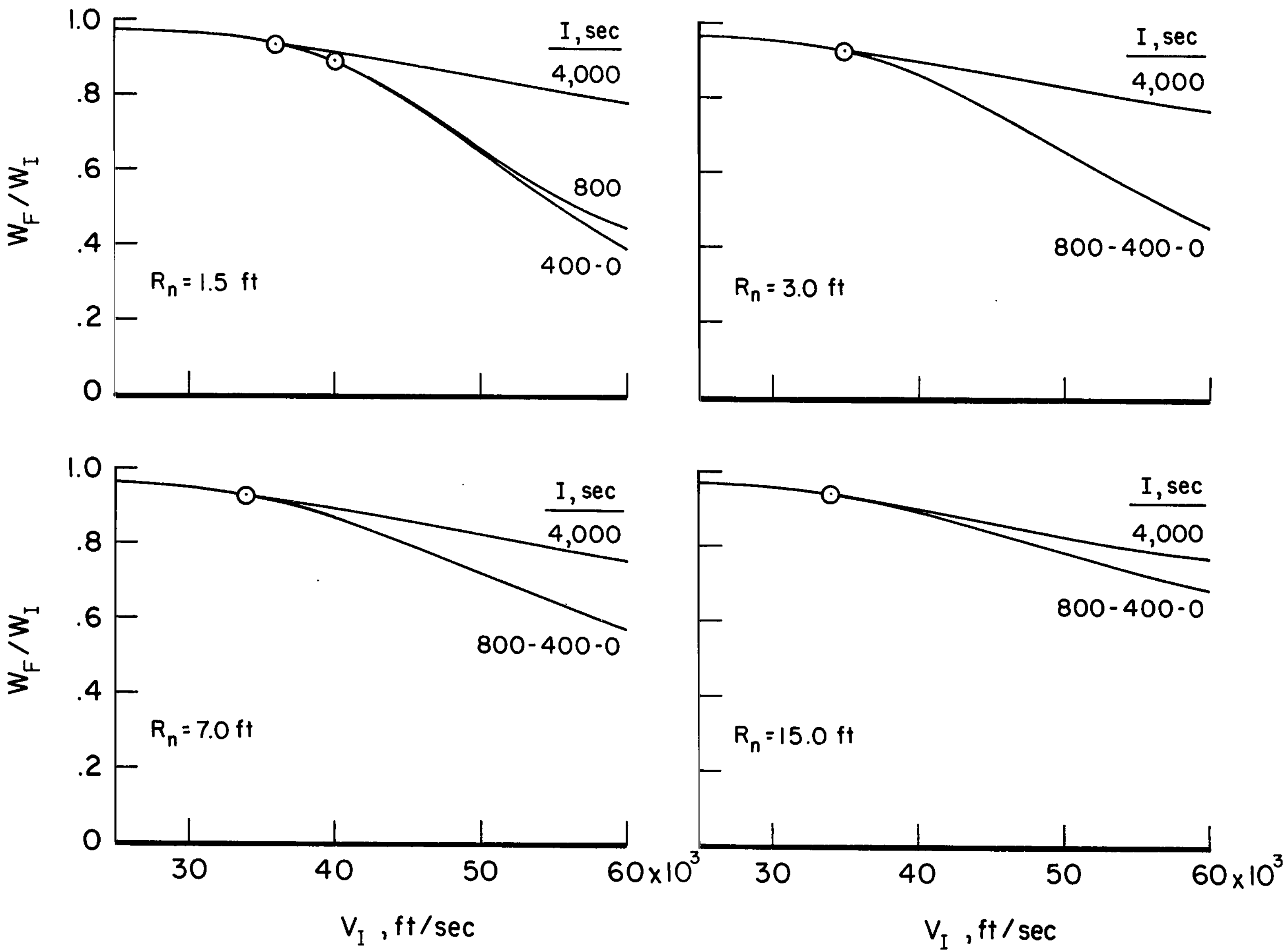
(b) $\frac{W_E}{C_D A R_n} \sin \gamma_E = 9.2 \text{ lb/ft}^3$

Figure 4.- Continued.



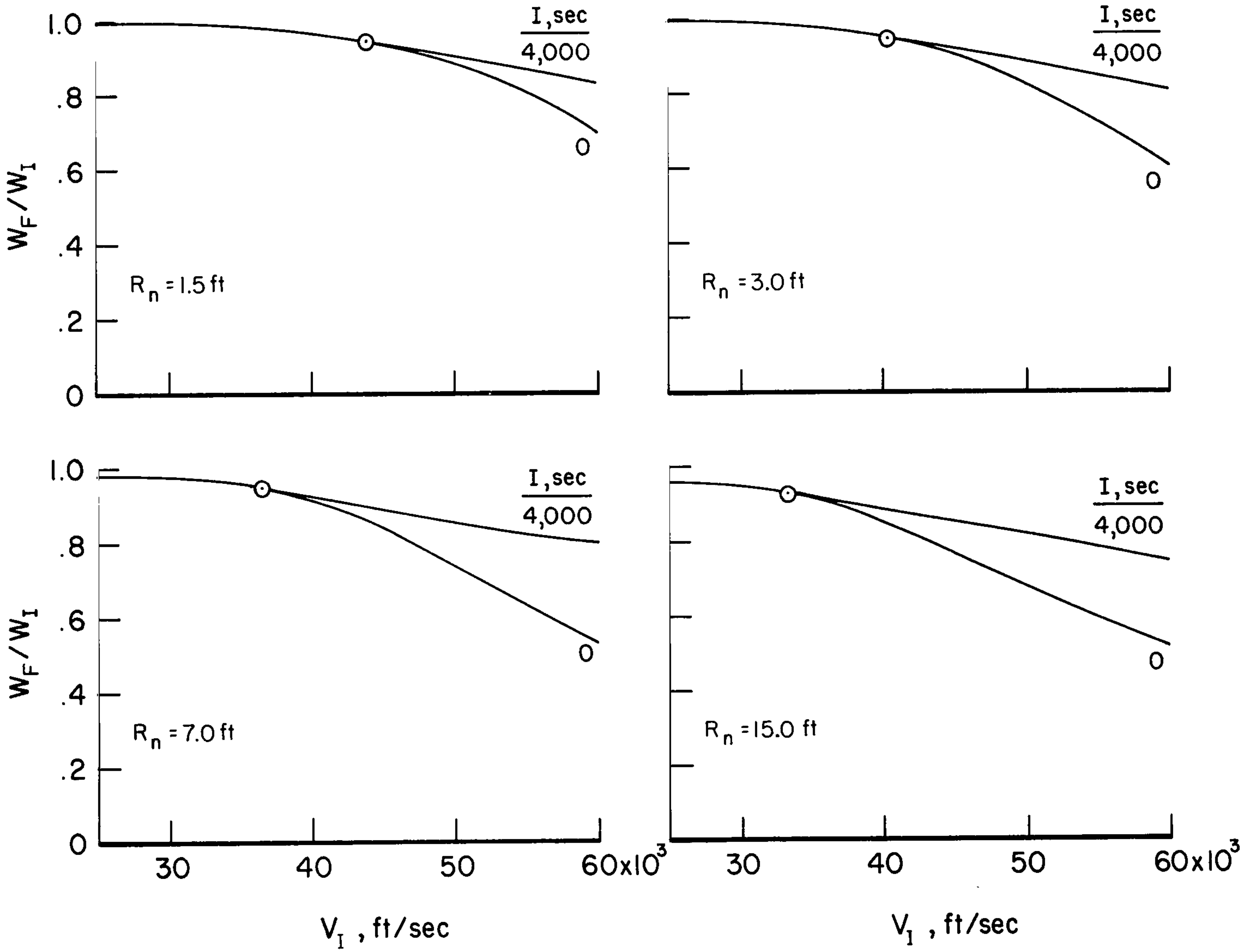
(c) $\frac{W_E}{C_D A R_n} \sin \gamma_E = 18.4 \text{ lb/ft}^3$

Figure 4.- Continued.



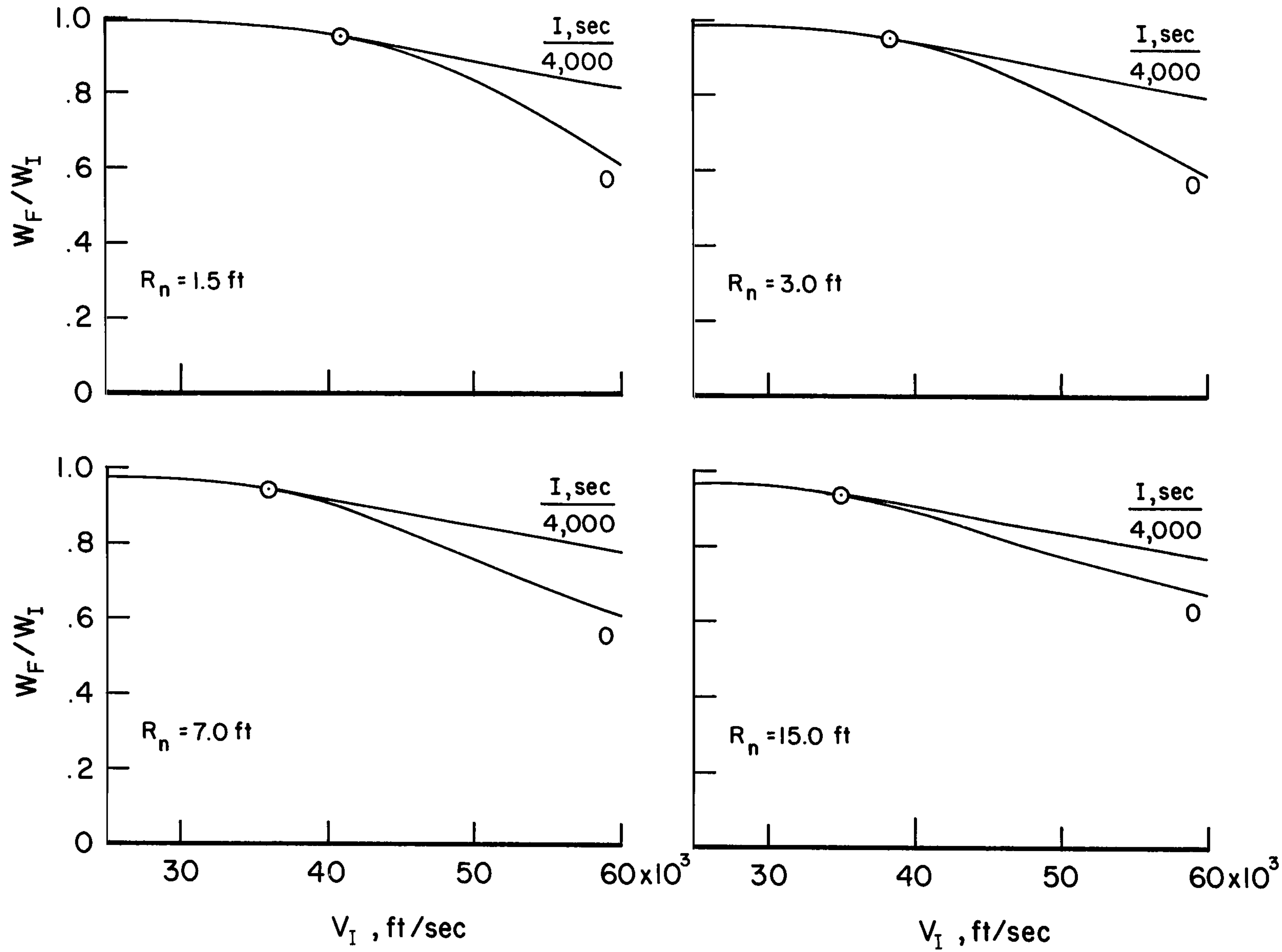
(d) $\frac{W_E}{C_D A R_n} \sin \gamma_E = 36.8 \text{ lb/ft}^3$

Figure 4.- Concluded.



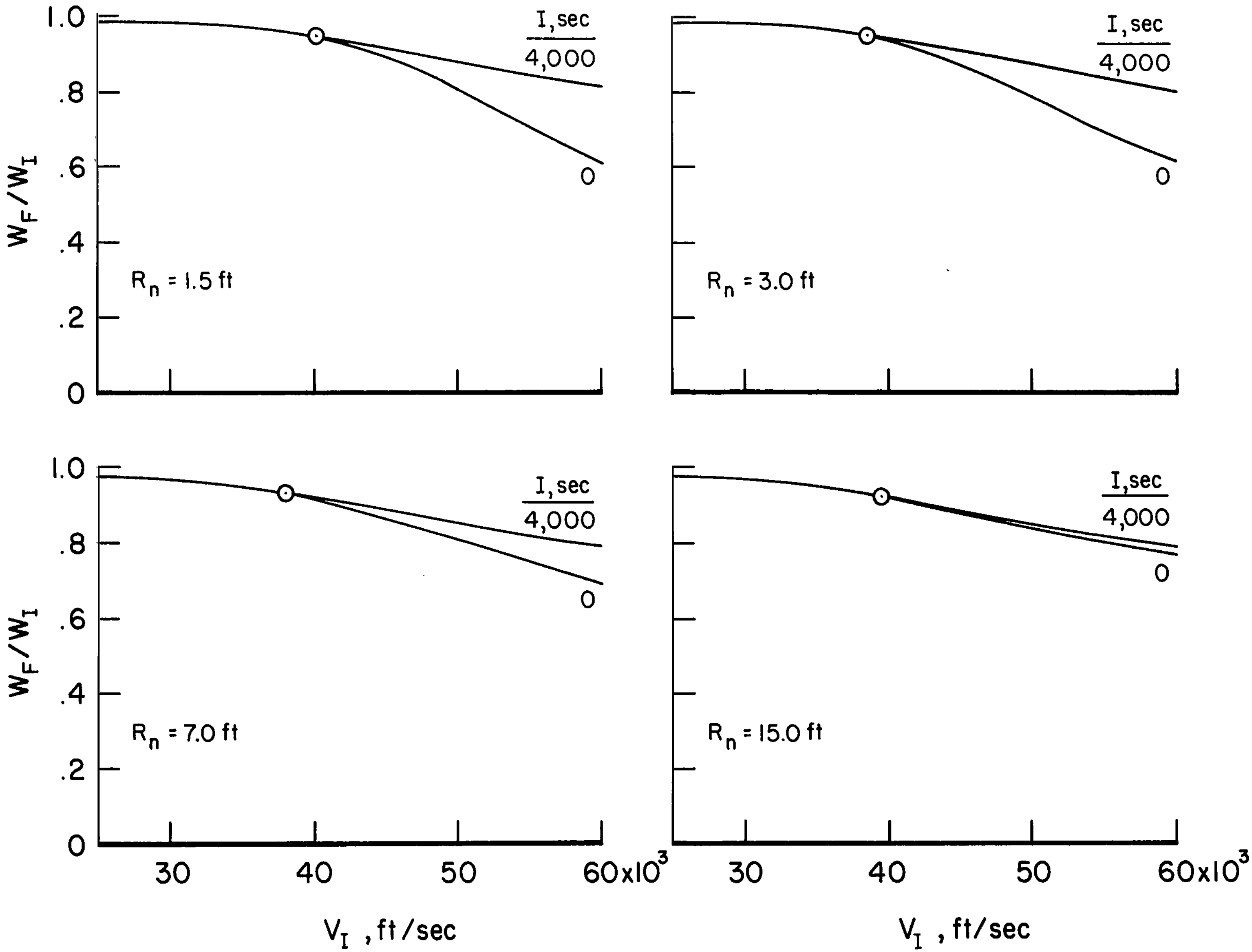
(a) $\frac{W_E}{C_D A R_n} \sin \gamma_E = 3.2$ lb/ft^3

Figure 5.- Weight ratios for aerodynamic braking alone, and for optimum combinations of aerodynamic and rocket braking; $\zeta = 20 \times 10^7$ ft^2/sec^2.



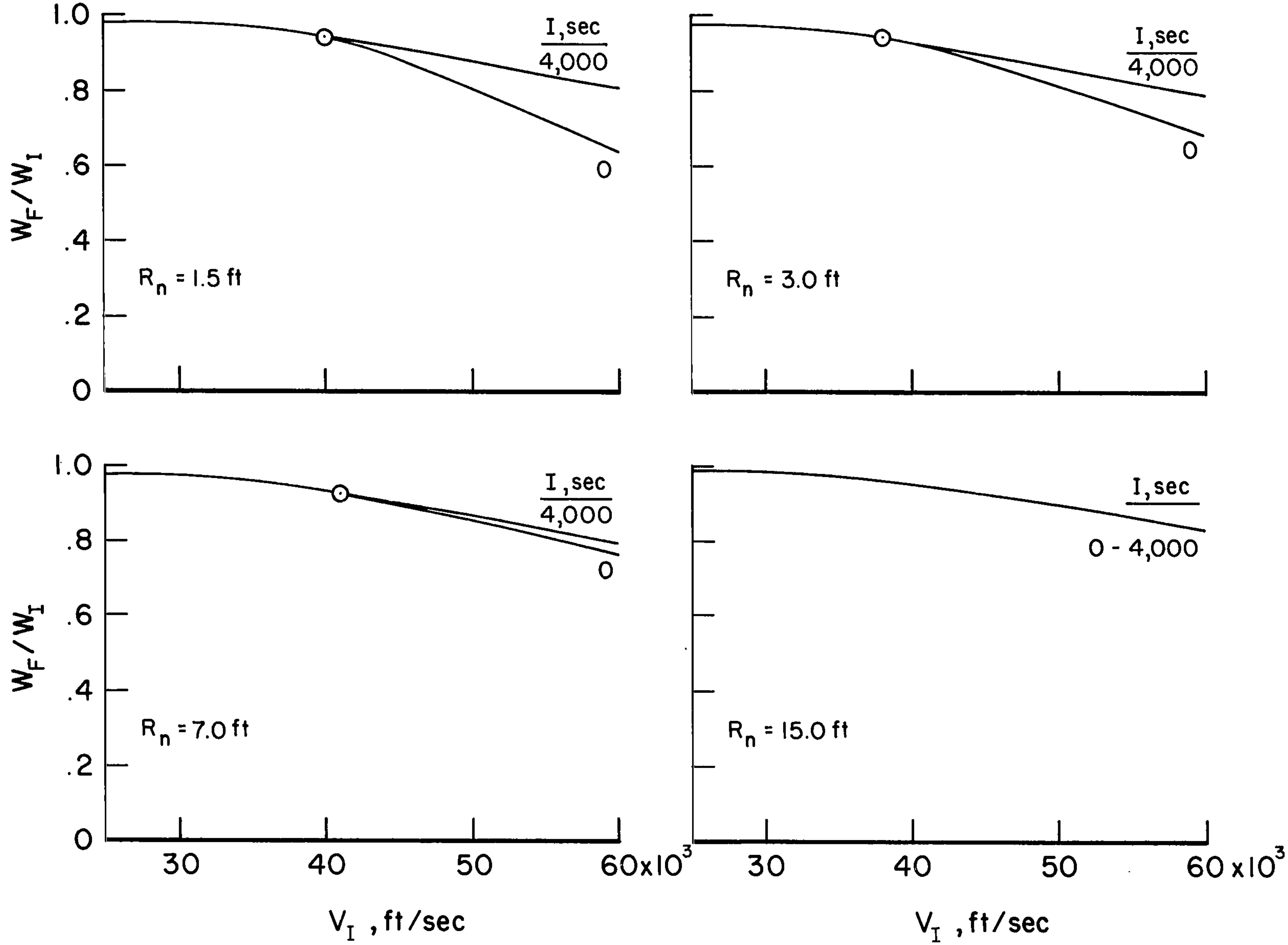
(b) $\frac{W_E}{C_D A R_n} \sin \gamma_E = 9.2 \text{ lb/ft}^3$

Figure 5.- Continued.



(c) $\frac{W_E}{C_D A R_n} \sin \gamma_E = 18.4 \text{ lb/ft}^3$

Figure 5.- Continued.



(d) $\frac{W_E}{C_D A R_n} \sin \gamma_E = 36.8$ lb/ft³

Figure 5.- Concluded.

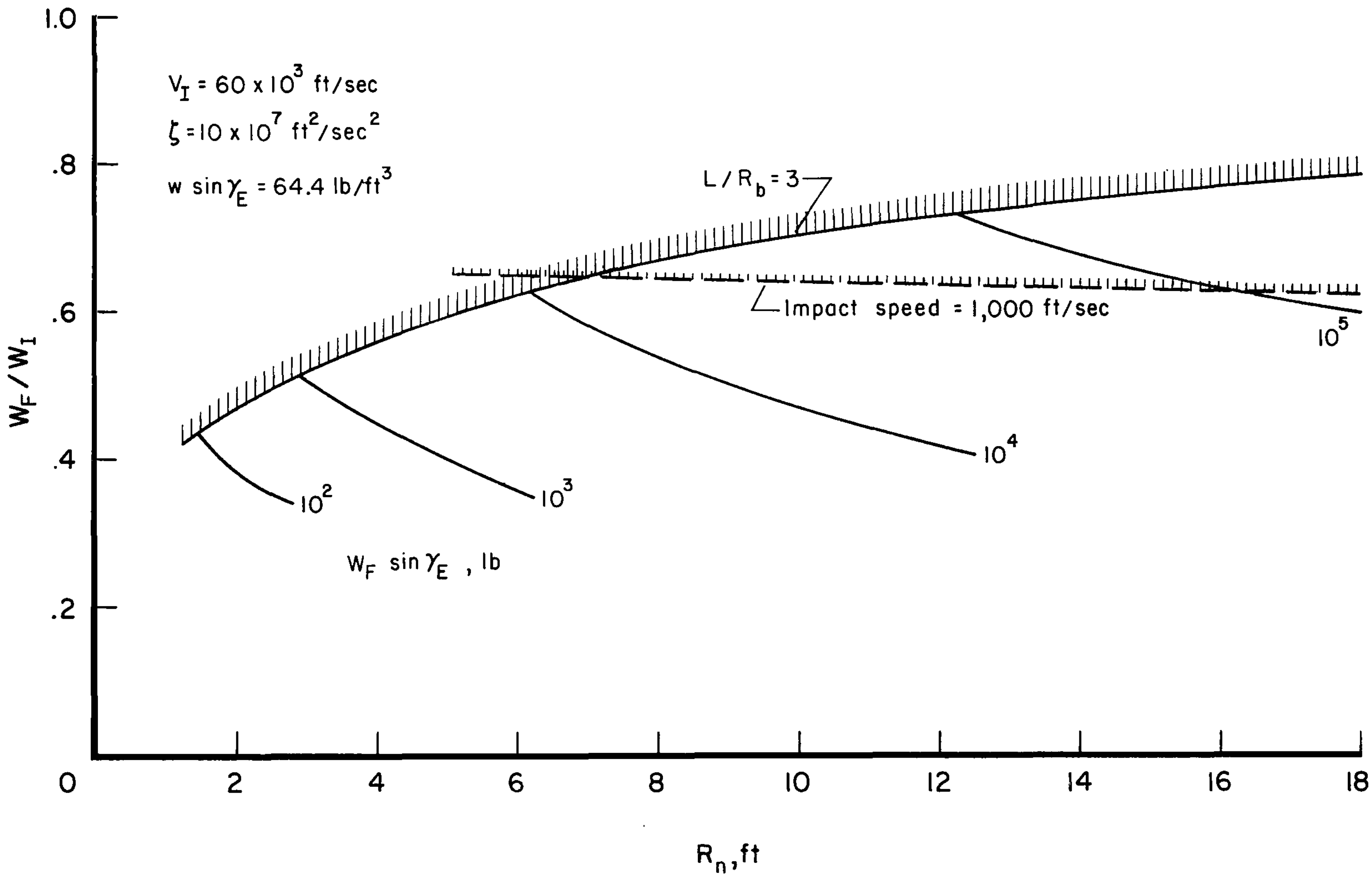
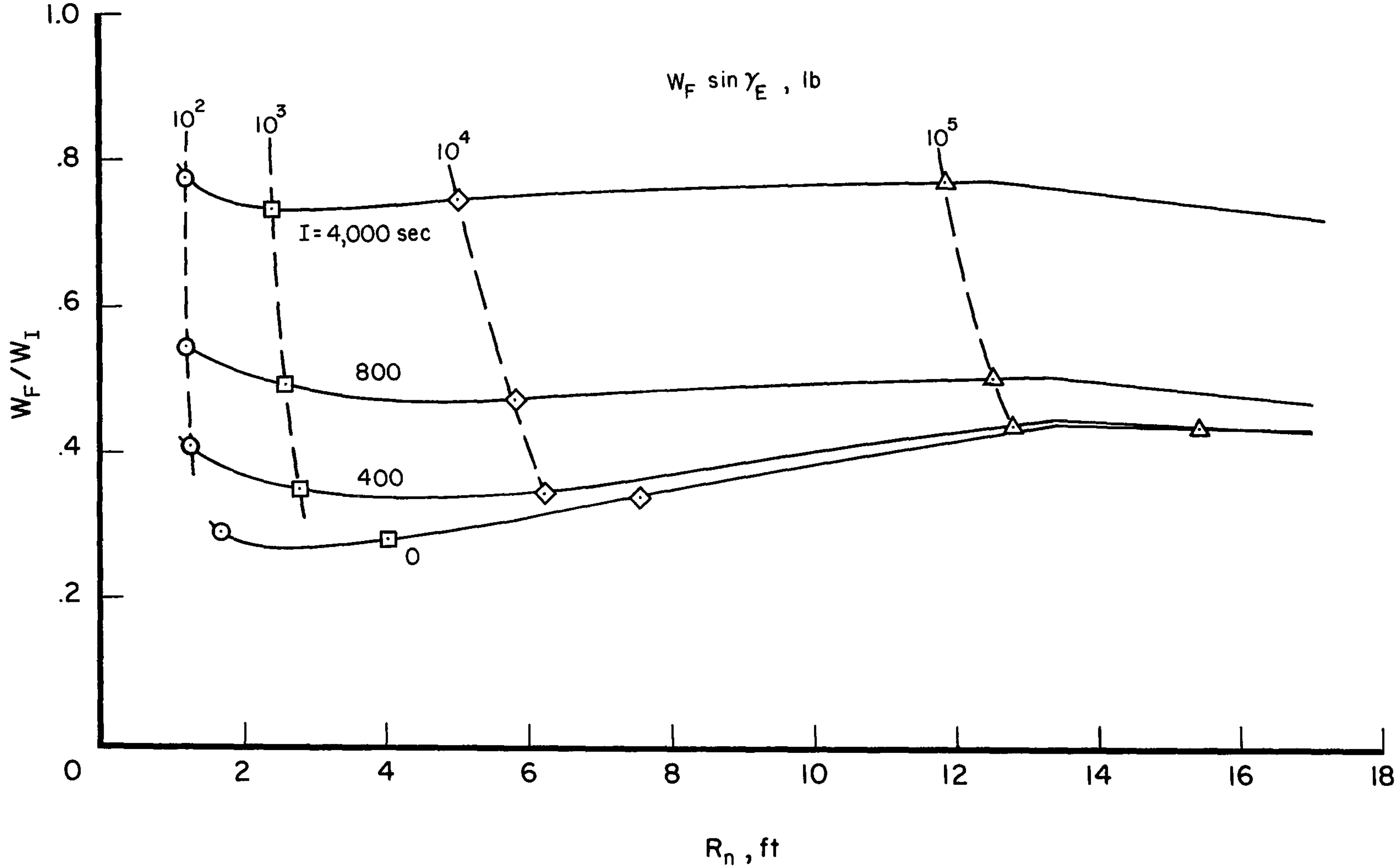
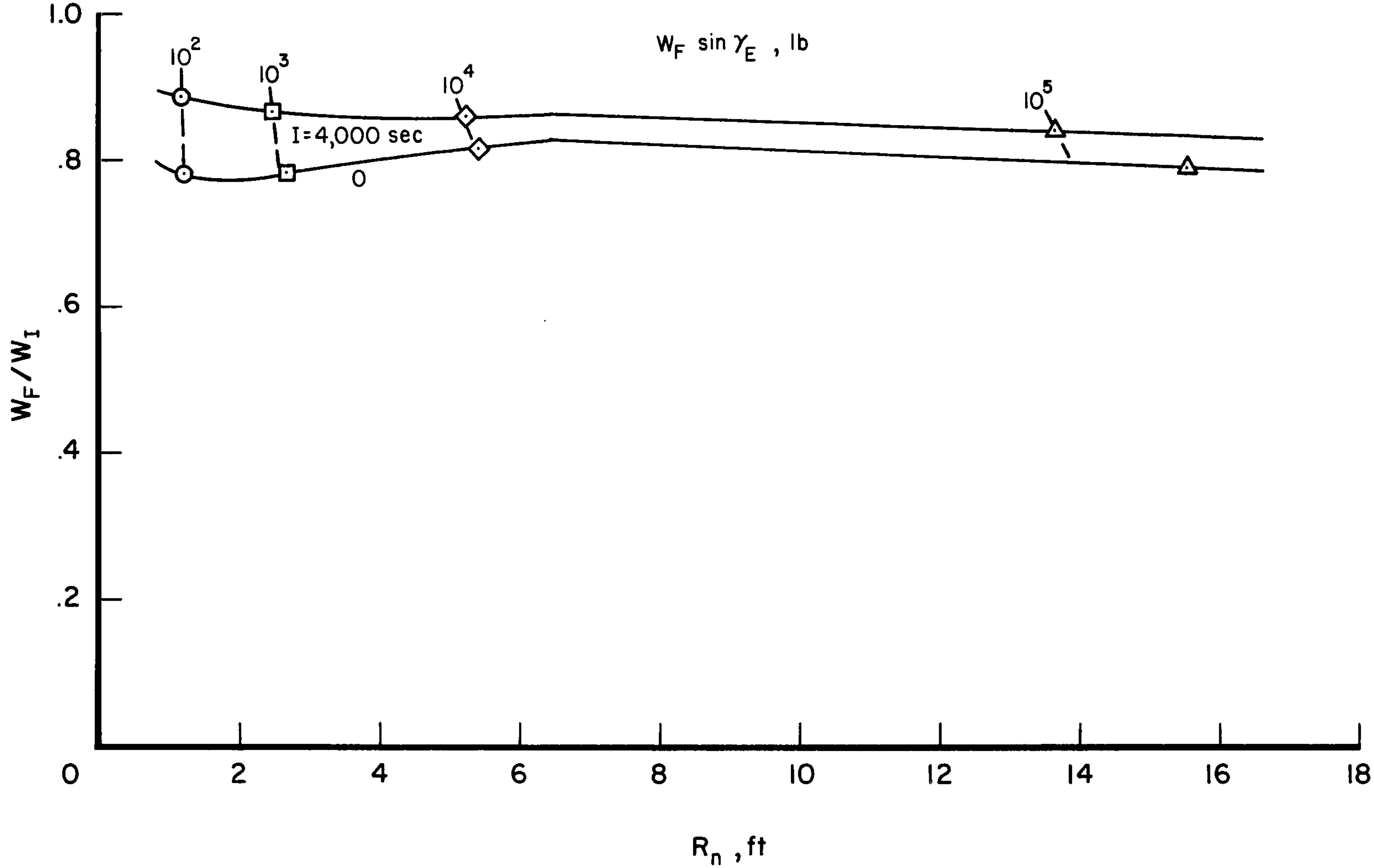


Figure 6.- Effect of nose radius on weight ratio for aerodynamic braking alone.



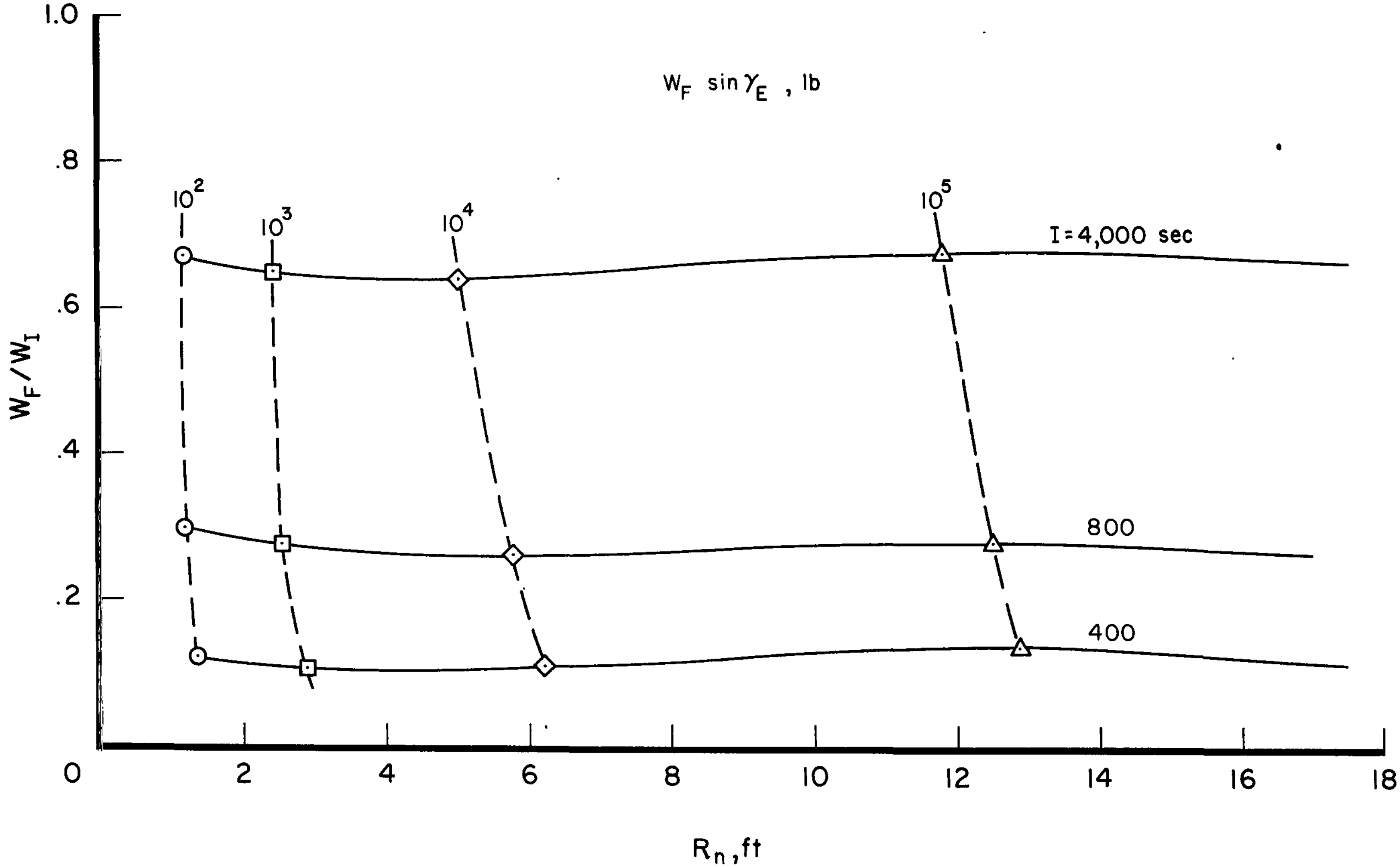
(a) $V_I = 45{,}000$ ft/sec, $\zeta = 2 \times 10^7$ ft^2/sec^2

Figure 7.- Effect of nose radius on limit values of weight ratio for aerodynamic braking alone and for optimum combinations of aerodynamic and rocket braking; $w \sin \gamma_E = 64.4$ lb/ft^3.



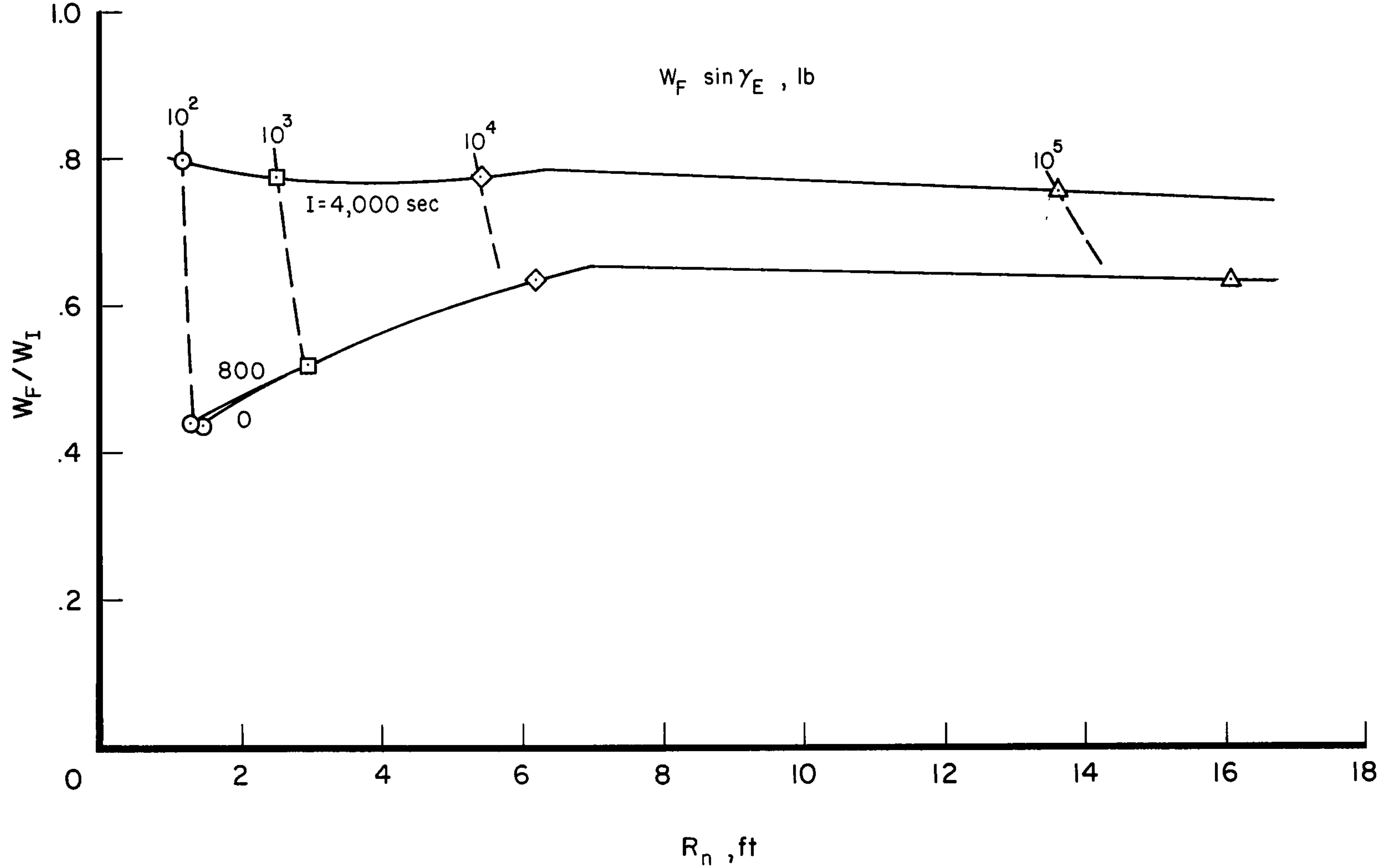
(b) V_I = 45,000 ft/sec, ζ = 10×10^7 ft^2/sec^2

Figure 7.- Continued.



(c) V_I = 60,000 ft/sec, $\zeta = 2\times10^7$ ft^2/sec^2

Figure 7.- Continued.



(d) V_I = 60,000 ft/sec, $\zeta = 10 \times 10^7$ ft^2/sec^2

Figure 7.- Concluded.

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